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U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TCREC TECHNICAL REPORT 61-118

SCALED VEHICLE MOBILITY FACTORS
(SCALE MODEL TIRES IN SNOW)

FOURTH INTERIM REPORT

Project 9R97-40-001-01, House Task 4.2

October 1961

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TCREC Technical Report 61-118

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The photographs shown as Figure 23 (page 26) should be identified as "FLOW FAILURE" in lieu of "SNOW FAILURE".

DEPARTMENT OF THE ARMY

TRANSPORTATION CORPS

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(Formerly Project 9-97-40-000, House Task 4.2)

SCALED VEHICLE MOBILITY FACTORS

(SCALE MODEL TIRES IN SNOW)

October 1961

Prepared by

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND

FORT EUSTIS, VIRGINIA

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SUMMARY

Tests have been conducted in snow with six reduced-scale tires. The tires
covered a wide range of width-to-diameter ratios. The results are expressed
in dimensionless terms and are applicable for a range of vehicle sizes and
weights as well as a range of dry snow conditions. Tests described in pre-
vious reports have covered the "flotation" type of performance. Tests de-
scribed herein cover the performance of two types of tires for the "ground-
supported" (limited snow depth) type of performance and, also, the results of
additional "flotation" tests. The complete "flotation" data, including that
from previous years' tests, are summarized and further analyzed. Present
data are limited to 4x4 vehicles with equal weight distribution. The possibility
is shown that data for vehicle tests in sand can be interpreted in terms of per-
formance in snow. Results of a preliminary snow survey, which can be used
to predict vehicle performance in subarctic, below-the-tree-line snow regions,
are shown in Appendix II.

CONCLUSIONS

It is concluded that:

1. Data in this report, covering the "flotation" and "ground-supported"
   types of performance, can be used as a design basis for 4x4 wheeled
   vehicles with equal weight distribution for a range of typical "difficult"
   snow conditions. The "ground-supported" results, however, are
   incomplete.

2. The scale-model techniques described herein are adequate for deter-
   mining the performance of wheeled vehicles in snow or sand; for
   example, to determine the effects of changes in wheel weight distri-
   bution or to determine the performance of articulated or train
   concepts.

(μ)

3. The snow-survey data provide tentative, but useful, data for predicting the performance of wheeled vehicles in the "difficult" subarctic, below-the-tree-line snow region.

BACKGROUND

The program for developing vehicle mobility scale-model tests for all types of soft terrain was initiated in 1956. The dimensional approach was chosen because the complexity of natural terrains is so great as reasonably to preclude useful solutions by primarily mathematical means, at least within the scope of the support for the program that could be expected.

The method followed was first to arrive at a basic understanding of the mechanics involved and then to conduct tests within a dimensional framework. By proper dimensional treatment, the results can then be interpreted in terms of performance of a wide range of similar vehicles of sizes different from the one tested and for a range of terrain conditions as well.

The test models were designed at first to be scale models of existing vehicles, and the tests were planned so that direct comparisons of the performance of models and full-size vehicles could be made. The scale ratios were made large (about 1:4), and the tests were performed in the field in natural terrains. This eliminated the problem of reproducing natural terrains in the laboratory; it also permitted direct comparison of the results of model and full-size vehicle tests made in the same real terrains of interest. This was desirable because natural terrains are generally highly stratified in horizontal planes, and this stratification is a characteristic that strongly affects vehicle performance. Tests performed in idealized laboratory soils may thus have represented unreal conditions or conditions that are not of interest and, of course, would not have permitted direct comparisons of models with full-size vehicles operating in the same terrain.

The relatively large scale ratios made the size of the models commensurable with the expected dishomogeneities in natural conditions, and minimized errors associated with any necessary neglect of proper scaling of secondary factors.

The first tests were made in snow with the locomotive unit of the Logistical Cargo Carrier (LCC) and a one-quarter scale model (Reference 4). The LCC locomotive is a 4x4, 30-ton vehicle utilizing 10-foot-diameter by 4-foot-wide tires. In light, subarctic-type snow, this heavy vehicle operates with ground support. Correlations were obtained between the model and full-size vehicle, primarily on the basis of snow depth, since the method of reducing snow depth for the model tests resulted in an essentially constant snow

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condition. The method for measuring effective snow strength with scaled-plate-penetration tests had not been developed at that time.

Further correlation tests in snow were conducted at Houghton, Michigan, during 1957 and 1958 with a lightweight "flotation" wheeled vehicle (Marsh Buggy) and a model of approximately one-quarter scale (Reference 5). In 1959, tires having a wide range of shapes were evaluated for "flotation" performance (Reference 8)

Correlation tests in sand were conducted with the one-quarter scale model of the LCC at Fort Story, Virginia, during the summer of 1956; results of these tests are reported in Reference 4.

Further correlation tests were conducted in sand with the Marsh Buggy and scale model at Fort Story, Virginia, during 1958, 1959, and 1960. Tests were also performed with a wide range of tire shapes. Results of these tests are reported in References 6, 7, and 9. Preliminary correlation tests with the Marsh Buggy and scale model have been conducted in marsh (Reference 1). The tests described in this report cover "ground-supported" performance tests in snow with two tire shapes and some additional "flotation" tests.

DESCRIPTION OF EQUIPMENT

Seven 24-inch- to 36-inch-diameter tires of different shapes were tested (Figure 1), six of which have been tested in snow. The tires were mountable on three chassis: a lightweight model chassis, originally the Marsh Buggy model chassis (Figure 2); a heavier model chassis, originally the LCC model chassis (Figure 3); and a 3/4-ton, 4x4 truck chassis (Figure 4). Gross weights from a minimum of 180 pounds to about 600 pounds (depending on the tires and rims used) could be obtained with the light model chassis, and up to 8,000 pounds gross vehicle weight could be obtained with the 3/4-ton truck chassis.

The two model chassis were originally built and tested as models of the Marsh Buggy and of the LCC lead unit (Sno-Train). In the tests covered by this report, the models were merely typical 4x4 configurations of vehicles with whichever shaped tires were mounted rather than models of any particular prototype The tread and the wheelbase of the models were unimportant in the type of tests undertaken, since in all cases, the tires were spaced sufficiently far apart to preclude any interaction.

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b.00-16, Single   Marsh Buggy   LCC   Torus

b.00-16, Dual   Rolling Bag   Rolling Bag
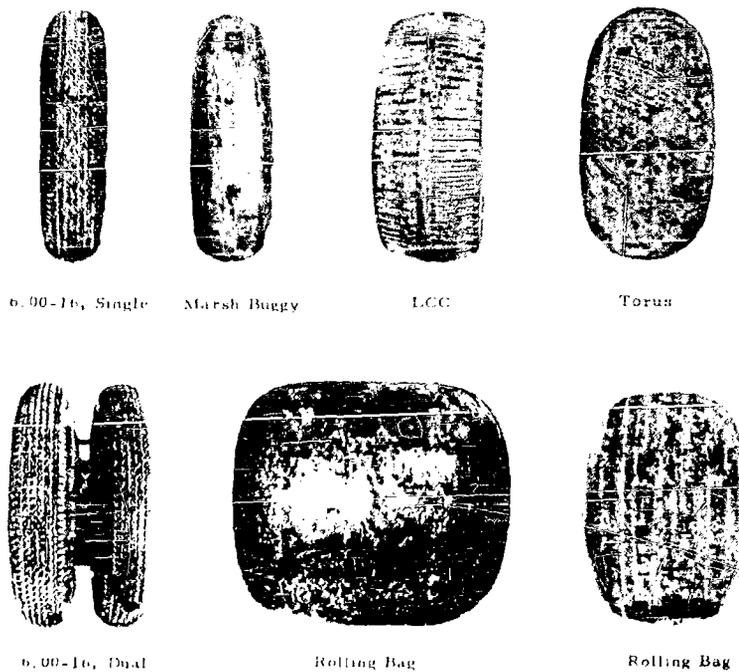
Figure 1. Types of Tires Tested.
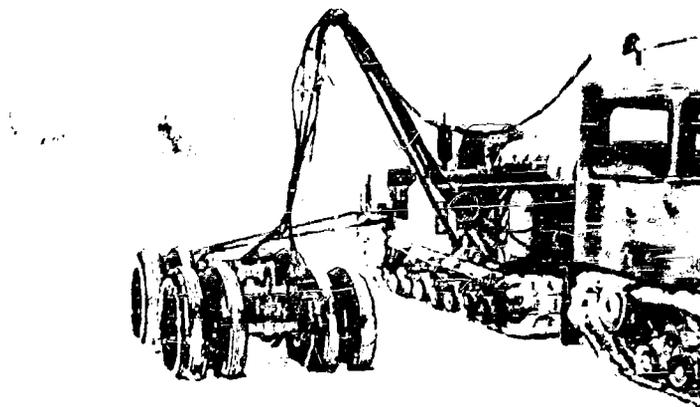
Figure 2. Marsh Buggy Model Chassis.

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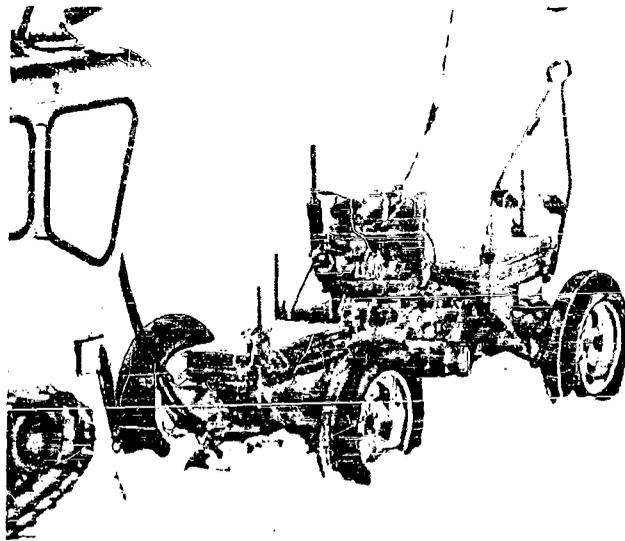
Figure 3. Logistical Cargo Carrier Model Chassis.

Figure 4. 3/4-Ton Truck Chassis.

Three full-size vehicles have been tested in snow to date: the Truck, Tank, Fuel, Logistical High-Mobility, 5,000-gallon-capacity, 4 x 4, XM438 15-ton GOER-type vehicle with 29.5-25 wide-base tires having a diameter of 73.4 inches (Figure 5); the lead unit of the LCC (Figure 6); and the Marsh Buggy (Figure 7). The LCC lead unit weighs 58,700 pounds and is a 4 x 4 vehicle with 120-inch-diameter wide-based tires. The tests for the LCC were
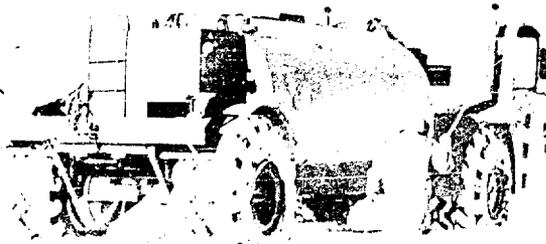
Figure 5.   Full-Size XM438 (Goer-Type
Vehicle).

Figure 6.   Full-Size Logistical Cargo Carrier
Locomotive.

performed in 1956. The Marsh Buggy weighs 11,000 to 15,000 pounds and
has tires 114.7 inches in diameter; the tests were performed in 1958. The
GOER weighs 34,775 pounds empty and 62,450 pounds loaded; the tests were
performed in 1960. The dimensions of the tires are shown in Table 1.
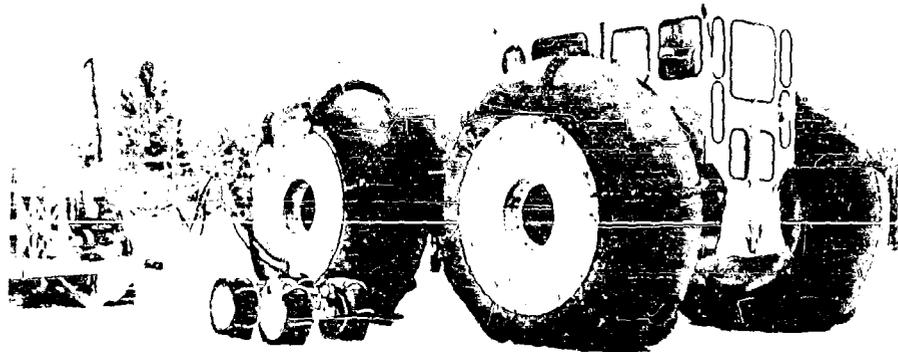
Figure 7. Full-Size Marsh Buggy and One-Quarter Scale Model.

TABLE 1
DIMENSIONS OF TIRES

Type of Tires	Outside Diameter (in.)	Section Height (in.)	Section Width (in.)	Width Divided by Outside Diameter
6.00-16, single	27.8	5.2	6.5	.23
Marsh Buggy, model	25.9	5.1	9.0	.35
LCC, model	29.9	6.1	12.0	.40
Torus type	34.7	14.5	17.0	.49
6.00-16, dual	27.8	5.2	14.6*	.52
24-24 rolling bag	24.3	8.5	24.3	1.00
36-22 rolling bag	36.0	11.9	22.5	.623
Marsh Buggy, full size	114.7	23.0	38.6	.34
LCC, full size	120.0	24.4	48.0	.40
GOER	73.4	20.7	31.5	.43

*Overall width of dual configuration (includes the 2-inch spacing).

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The tires have a wide range of cross-sectional shapes. The LCC and GOER tires are typical of a low-profile type of tire; the rolling-bag-type tire has, in effect, a low-profile or "flattop" shape. The remaining tires are more or less round-section tires.

The tires have a varying relation of rim width to tire section. The Marsh Buggy-, GOER-, and LCC-type tires are wide based; the torus-type tire, which is a true torus with a center diameter of zero, could be considered narrow based. The 6.00-16's are mounted on 4-1/2-inch passenger car rims.

The tires had varying degrees of carcass stiffness. The torus-type and the Marsh Buggy model tires were somewhat flexible. The 6.00-16 tires, which were made especially to a reduced ply rating, were the most flexible. The rolling-bag and the LCC-model tires were stiff in comparison to the others. Tests were conducted at equal deflections on a hard surface (in terms of percent of outside diameter) by adjusting the inflation.

None of the tires tested (except the LCC type) were specially designed or constructed for this program except in minor, inexpensive detail. All except the LCC model tires were available without any investment in special molds, and selection was made on the basis of obtaining the widest possible range of shapes and proportions from among tires made in available molds.

TEST PROCEDURES AND RESULTS

PROCEDURES

The procedures and the dimensional framework for conducting and inter-preting these scale-model tests have been developed through test programs in sand, snow, and marsh; direct comparisons of models and full-size vehicles were included (References 1, 4, 5, 6, and 8). The following is a summary of the procedures and dimensional framework discussed in the Second Interim Report (Reference 8).

The interpretation of the results of the scale-model tests depends on a proper dimensional analysis. A complete list of the vehicle and soil factors, and the numerics they form, has been made. Through field test programs that involved comparisons of the performance of models and full-size vehicles, these numerics have been reduced in number to only those that importantly influence the performance of the vehicle.

The following symbols are used in the numerics:

b	=	overall tire width
c_e	=	effective structural cohesion of the aggregate snow stratifications involved
c_r	=	relative effective structural cohesion as determined by plate tests
c_s	=	precollapse structural cohesion
D	=	drawbar pull
d_p	=	plate diameter
d_w	=	tire diameter
f	=	rubber-to-snow friction
h	=	snow depth
q	=	average pressure
S	=	slip ratio
W	=	vehicle weight
z_p	=	plate sinkage
z_w	=	vehicle sinkage
ϕ	=	angle of internal friction determined from postcollapse dynamic shearing resistance
γ	=	density of snow

Functional equations for operation of vehicles in sands, dry snows, and other primarily frictional materials have been validated for "flotation" and "ground-supported" performance. For "flotation" performance, where the depth of the snow (or soil) can be considered indefinitely deep, such that the collapsed or deformed layers of snow do not extend to the ground (or, in soil, to an underlying layer of hardpan), the equations are as follows:

$$\frac{D}{W} = f^i \left(\frac{W}{c_s d_w^2} , \phi, \ S \right) \tag{1}$$

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$$\frac{z_w}{d_w} = f^{ii} \left(\frac{W}{c_s d_w^2}, \phi, S \right) \qquad (2)$$

Sinkage must be correlated in order to maintain the geometric similarity of the vehicle-soil systems presumed throughout the analysis. For "ground-supported" performance, where the collapsed layers extend to the ground (or underlying hardpan), depth is an important variable and is considered, as shown in the following equations:

$$\frac{D}{W} = f^{iii} \left(\frac{h}{d_w}, \frac{W}{c_s d_w^2}, \phi, S \right) \qquad (3)$$

$$\frac{z_w}{d_w} = f^{iv} \left(\frac{h}{d_w}, \frac{W}{c_s d_w^2}, \phi, S \right) \qquad (4)$$

Since the sand or snow pack is not a homogeneous material but is stratified (each layer with its own properties), it is not possible to assign a single value for the structural cohesion, c_s.

Plate Penetration Tests

A test is used to determine a relative effective value of the structural cohesion, c_r, for the aggregate material to the depth that it is utilized by the vehicles. The resistance to the penetration of round plates forced into the snow or sand at a steady rate is measured. The diameters of the plates are scaled to the size of the wheel diameters of the vehicles. The assumptions are made--validated by direct comparisons of model and prototype tests-- that there is an effective value of the structural cohesion, c_e, which, if substituted in the load numeric $\frac{W}{c_s d_w^2}$, will correlate the results, and that the relative effective value, c_r, determined by forcing correlation of scaled-plate test results, is proportional to the effective value of the mechanical property.

The scaled-plate test results--with the plates scaled according to the wheel diameters--reflect size effects in the failure of the snow because of its natural stratification. The plate tests are, actually, a scale-model test. If plates of various sizes are tested to a sufficient depth of penetration, each will sample the snow to approximately the depth that its corresponding wheel size will utilize.

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The tests were made with a hydraulic cylinder that pushed the plates into the
snow at a steady rate (Figure 8). The force and sinkage were recorded di-
rectly on an X-Y recorder in terms of pressure and of sinkage ÷ plate dia-
meter.
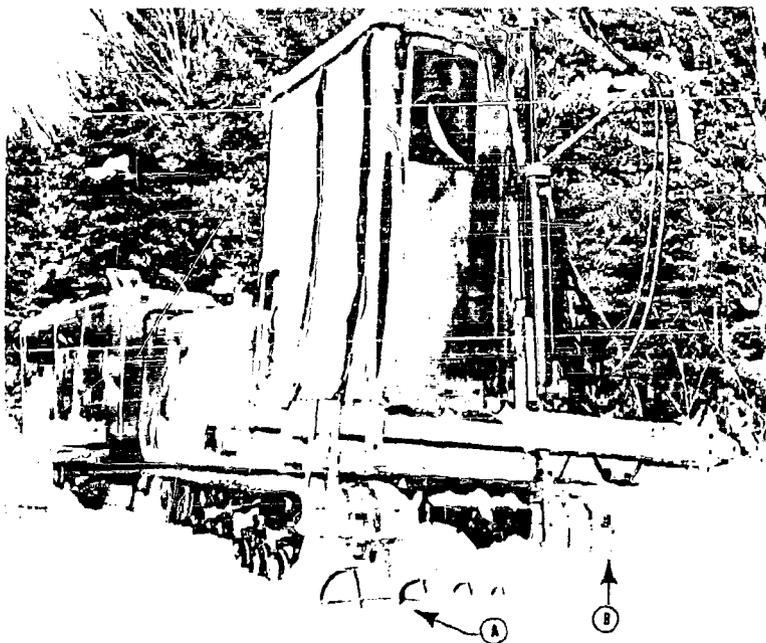
Figure 8. Snow and Soil Analyzer. Note Shear Vanes (A)
and Scaled Plate (B).

Since the curves are not straight lines, their shapes must be considered.
Many tests in Canada and Michigan have shown that the typical "difficult"
subarctic snow packs of interest will generally have similar shapes. A
preliminary standard-shaped snow curve has been defined and designated
Type I, which is representative of many deep, dry, mid-season, below-
the-tree-line snow packs (Figure 9). On the basis of the data available to
date, * this curve represents the weakest snow likely to occur for no more

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*A limited survey of snow conditions in the tree belt of Canada, from the
maritime zone to western Ontario, was made during the 1959-1960 snow
season. Results of this survey, as well as accumulated test-site data
from previous years, are shown in Appendix II.
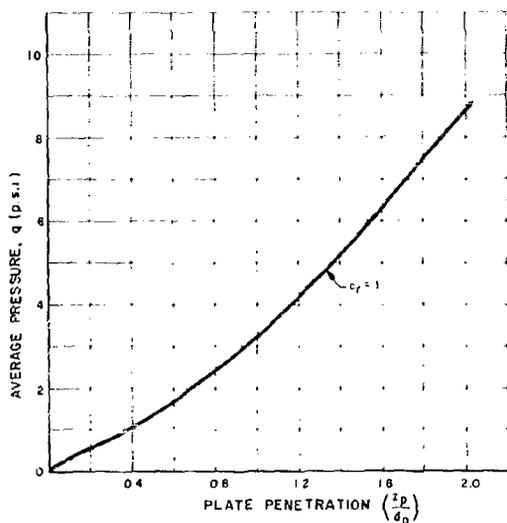
Figure 9. Typical "Difficult" Type I (Dry, Below-the-Tree-Line) Snow, Measured by 12-Inch Diameter Plate.

than a few days in one winter, as measured by the 12-inch plate; this snow has been assigned the value of $c_r = 1$ and is designated as "difficult" Type I snow.

The curves from each plate test were compared with the standard "difficult" Type I curve. If the point-for-point ratios with the Type I curve were nearly the same at every dimensionless depth (i. e., if the curve had the same shape), then the snow was considered to be Type I with a c_r corresponding to the average ratio (Figure 10). (If the shape is not almost the same, the model test can not be expected to correlate with other tests in Type I snow, as the geometric similarity of the vehicle-snow system would not be maintained.) The method worked well even when the test curve was not closely related to the standard curve, although the basic philosophy of the
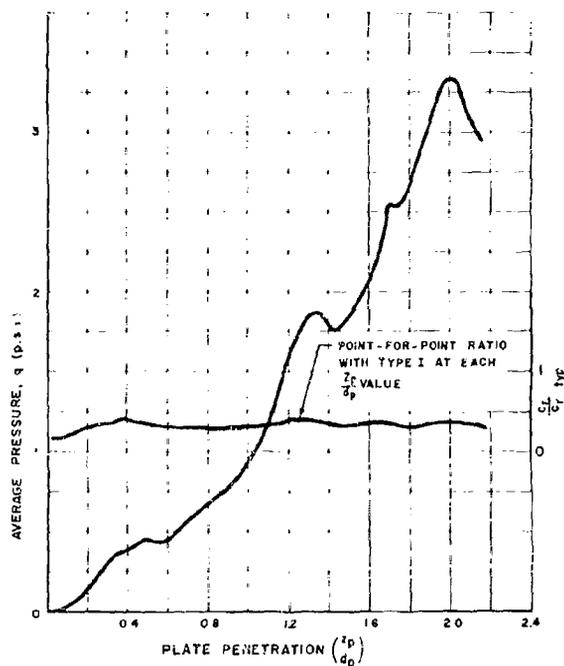
Figure 10. Ratio of Actual Plate Test to Type I Curve.

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method would suggest that when the shapes were not similar, correlation should not be expected a priori.

The plate tests were performed almost simultaneously with every vehicle test at two or more locations along the test lane and were repeated three or more times at each location. The homogeneity of the snow, as indicated by reproducibility of the plate tests, was generally good. Figure 11 is typical.
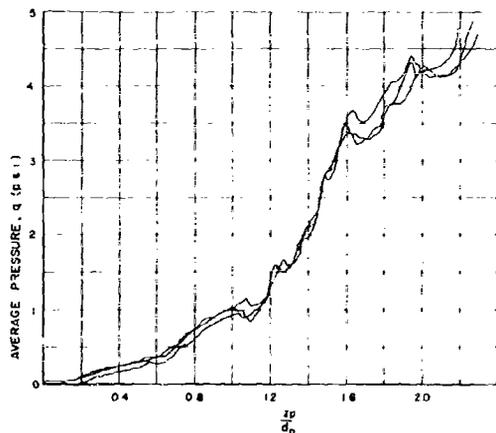
Figure 11. Typical Reproducibility of Plate Data to Indicate Homogeneity of Snow.

Wheel diameter ÷ 10 has been used in earlier "flotation" tests as the standard scaled-plate size and was used again for the 1960 "flotation" tests. For the "ground-supported" tests, which were the principal objective of the 1960 program, it was realized that a plate scaled as wheel diameter ÷ 10 would be affected by its proximity to the ground when the plate reached a certain depth.* Accordingly, for the "ground-effect" tests, measurements were made with a plate size of wheel diameter ÷ 25, which could penetrate nearly the entire snow depth without "ground-effect". "Ground effect" was assumed to begin at nominally one plate diameter from the ground. When c_r was determined for the "ground-effect" tests, the data were considered only up to that penetration. In order to utilize the "standard" Type I snow curve with a minimum distortion (because of a change in the "standard" plate-to-wheel-diameter relationship), it was arbitrarily decided that sinkage, for comparison with the Type I curve, should be expressed in terms of $\dfrac{z_p}{2.5d_p}$ (actual plate). In effect, the pressure experienced by the smaller plate was assumed to be about the same as that for the larger "standard" plate at the same actual penetration in inches. All of the "ground-supported" performance test data are presented with measurements made with the smaller plates.

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*This was not a problem for the "flotation" tests, since these tests were made on sufficient snow depths to be independent of the ground.

Other Snow Measurements

Nakaya roaring-bonfire profiles were made for each test in accordance with the procedures described in Reference 8. (See Figure 12.) An attempt was made to identify data scatter in terms of the character of snow failure as observed from these pictures.
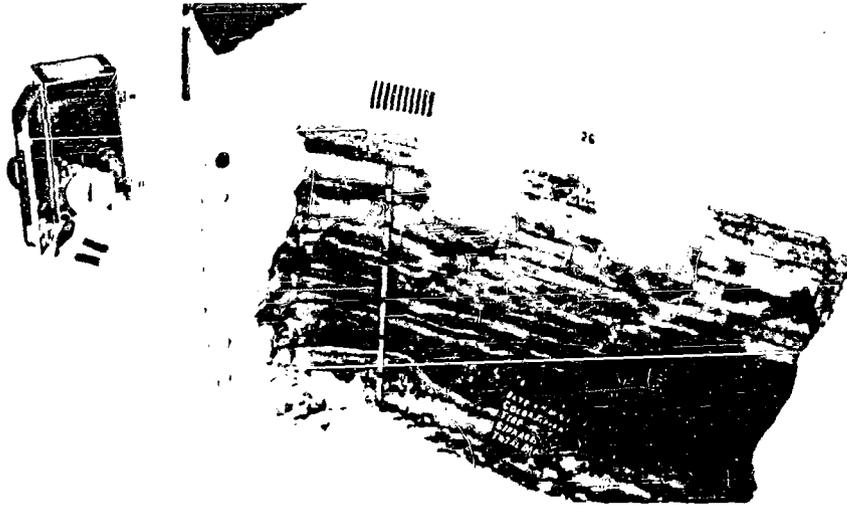
Figure 12. Nakaya Bonfire Profile. Descriptive Snow Measurements.

The snow was identified further by the following methods, which had been widely used earlier (Reference 2): density, temperature, descriptive classification, and Canadian Hardness. All measurements were made in profile (Figures 12 and 33).

The dynamic shearing resistance was measured with circular shear heads. The shear heads had four 3/4-inch-high radial dividers at right angles and a circular limiting lip of the same height. To clarify the results obtained from these tests, shear heads were used with 10-, 25-, 50-, 100-, and 200-square-inch areas (Figure 8). A new apparatus was used, which resulted in a procedure different from that of previous years. Normal loading was applied by a continuous penetration of the shear head rather than in increments by dead weights. While it was intended to employ both procedures, the new apparatus was not amenable to the dead-weight procedure.

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Performance Tests

The performance was measured in terms of drawbar pull and sinkage versus the slip ratio on level snow.

"Flotation" tests were made with the following types of tires: the 6.00-16, single; the LCC; and the 24-24 rolling-bag type tires, in order to further establish the "flotation" performance curves obtained in the 1959 tests. "Flotation" data accumulated from previous tests are discussed and presented in this section under "Results" and in Appendix II.

"Ground-supported" model performance tests were conducted by scaling the snow depth to approximately 0.1 to 0.3 of the wheel diameters and by performing tests over a wide range of model weights.

A special snowplow was developed for scaling the snow depth. A procedure that had been developed for the 1956 scaled-depth tests employed two types of road plows in combination. While the method proved to be satisfactory, it involved the rental of two snowplows that were only obtainable on an as-available basis. The "depth-scaling snowplow" was capable of controlling the desired depth more accurately and was available on a continuous basis (Figure 13). The rotary snow blowers are positioned in height between the
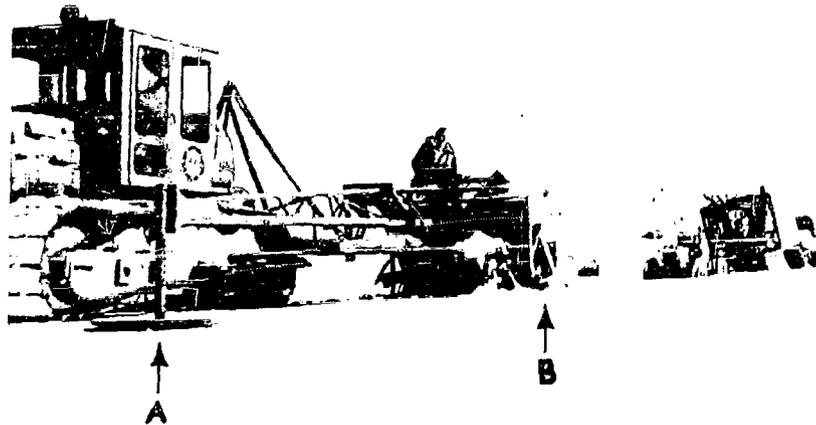
Figure 13. Depth Scaling Snowplow Used for Scaled-Depth Model Tests. Cutters Are Indexed Between Pan (A) and Disc Wheels (B).

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two large steel disc wheels and a pan on an extended boom. The disc wheels cut to the lowest surface, and the pan rides on the surface of the snow; the snow blowers are then positioned in reference to these two levels by means of a hydraulic cylinder. Operation of this snowplow is limited to paved surfaces, as the disc wheels would sink in unfrozen ground. A smooth, level hardstand surface is also required to obtain a uniform depth of snow; an unused airstrip was used for the tests. A plowed field or a field with clumps of grass, e.g., would introduce variations and uncertainties in the depth that would be substantial in relation to the reduced tire sizes.

Unfortunately, the 1959-1960 snow conditions were not as favorable for the scaled-depth tests as those that existed for the 1956 tests. In 1956, the lower layers of snow were quickly covered by subsequent snowfall and then underwent a metamorphosis that reduced them to a remarkably uniform, coarse-grained condition. Subsequent snowfalls protected this snow from further ephemeral changes or dishomogeneities that result from wind or thawing weather, and the snow remained in a constant homogeneous condition until the spring thaw. The early 1959-1960 winter snowfalls, however, were subjected to thawing temperatures before they were adequately covered by subsequent protective snowfalls; the ideal test conditions in the lower pack, as were discovered in 1956, did not develop.

During the 1959-1960 tests, the airstrip was plowed clean in the hope that the next snowfall would be protected by still subsequent snowfalls and that the snow pack would be able to complete its aging process protected from surface changes. This process was necessarily repeated two more times.

The snow pack that was finally utilized was of only partial depth. The layers that were used, after scaling, had accumulated from drifting snow and did not have sufficient covering layers or time to complete the aging and natural homogenizing process. The result was a varying strength condition, and the depth was uncertain because of the presence of a thin, hard crust of varying thickness near the bottom of the snow pack. Because of these adverse circumstances, only the best portions of the airstrip were utilized, and the number and accuracy of the tests that could be performed were considerably reduced. Had more ideal conditions prevailed, a complete range of tests could have been performed with all seven of the model tires. Because of the limited number of tests that could be performed, model tests were performed only with the 6.00-16's and the LCC-type tires.

The general procedure for the model tests was to cut to the desired depth a test course of snow for approximately 100 yards. Tests were then conducted on this strip with several weights. Data points were identified by colored stakes placed in consecutive sequence. The sinkage, snow depth, and plate test measurements were later keyed to each data point. All of the

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tests were performed for a constant tire deflection of 3.3 percent of the outside diameters. Tire deflections were measured on a hard stand.

Tests of full-size vehicles were conducted with the GOER vehicle on natural full-depth snow. The GOER tires had approximately the same proportions as the LCC tires.

RESULTS

"Ground-Supported" Tests

Because of the poor snow conditions, the "ground-supported" tests of the model tires were limited to the 6.00-16's and the LCC model tires. The LCC model tires were given first priority becuse the full-size GOER vehicle, which was equipped with tires nearly similar to the LCC type, was available for model/full-size comparison tests. (Also, results of both full-size LCC and model LCC tests were available from 1956 tests (Reference 4.) While the plate test for determining c_r had not been developed at the time of the 1956 tests, the 1956 descriptive data (i.e., density and Canadian Hardness) were matched with the 1959-1960 data and a value of c_r was assigned to equal that of the snow with the closest descriptive match. Tests were also made in 1956 with 7.00-16 tires mounted on the LCC chassis (Figure 14). Data from the 7.00-16-tire tests were handled in the same way and are reported with the 6.00-16 data.

The results of the scaled-depth tests are shown in Appendix I and in Figures 15 and 16. Constant snow-depth curves were faired to obtain the best fit with the data points.

Drawbar-pull data are reported at 25-percent slip, which approximates the slip at which maximum drawbar pull occurs. This is on the conservative side for predicting marginal performance; at the lower levels of performance, the drawbar pull reaches a maximum at 40- to 50-percent slip. Also, the tests were made at 3.3-percent deflection of the outside tire diameters. Performance will be somewhat better at maximum deflection, which will be approximately 6 to 10 percent (or 30 percent of section height) for the various tires (Reference 9).

The intercept of the limited-snow-depth curve with the "flotation" curve was determined from 1959 "flotation" test data (Figure 17). The critical snow depth (depth at which ground support starts) was determined from the disturbed or deformed bulb of snow visible from the Nakaya bonfire pictures.

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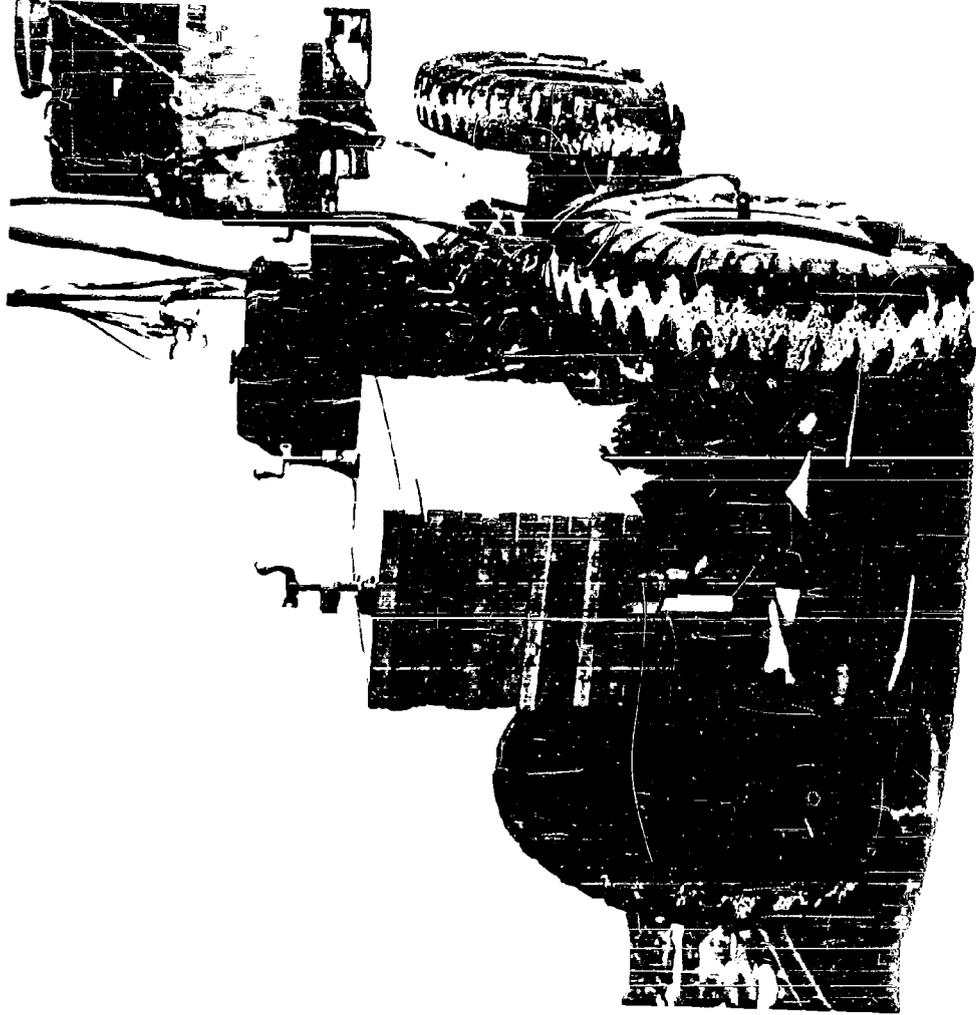
Figure 14. Logistical Cargo Carrier Model With 7.00-16 Tires.

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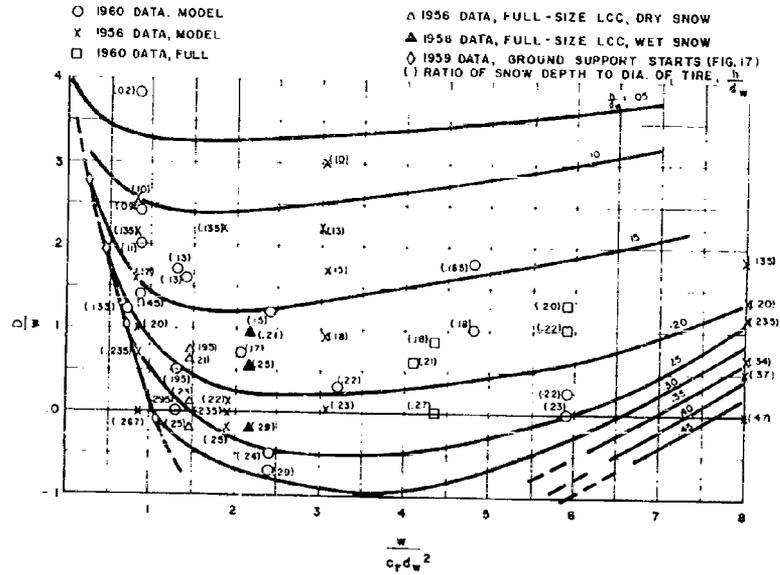
Figure 15. Results of "Flotation" and "Ground Support" Scaled-Depth Tests (LCC-Type Tires).
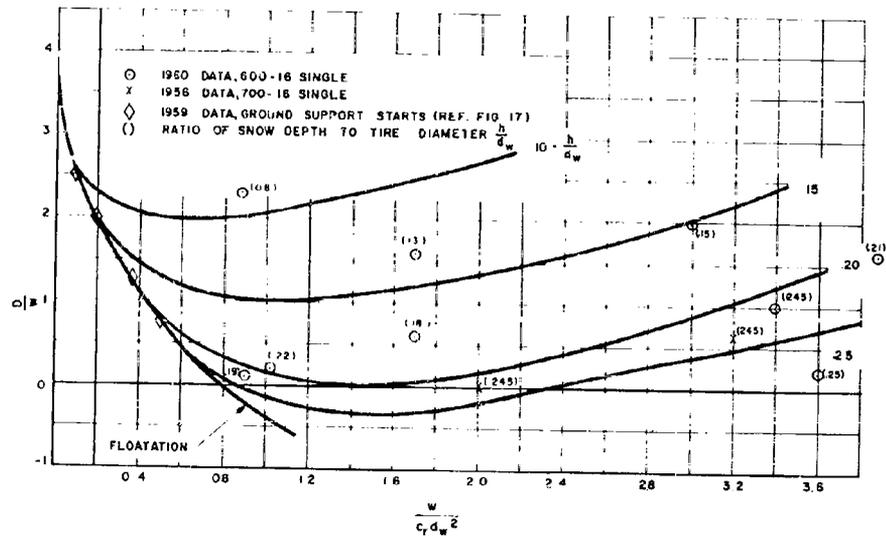
Figure 16. Results of "Flotation" and "Ground Support" Scaled-Depth Tests (6.00-16, Single-Type Tires).

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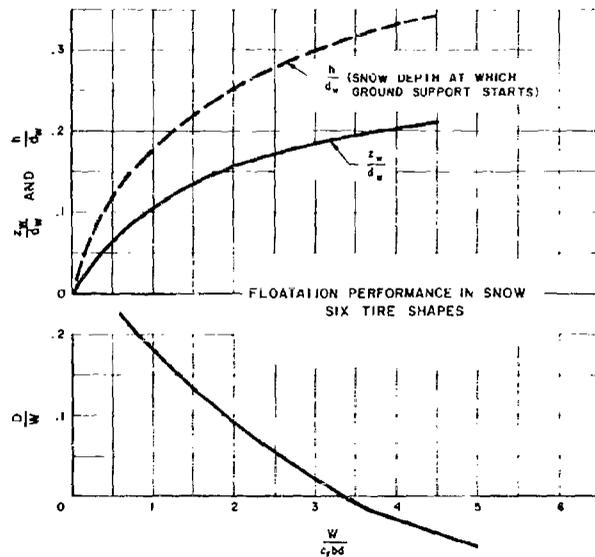
Figure 17. 1959 "Flotation" Data.

The results of tests with both tires are also shown in Figure 18, with the numeric $\dfrac{W}{c_r d_w^2}$ replaced with its dimensional equivalent, $\dfrac{W}{c_r b d_w}$ where b is overall tire width. The narrower tires show a somewhat better comparative performance. After their minimum point is reached, their performance improves at a faster rate, either as weight increases or as snow strength decreases.

Of particular interest in these data, and in the more complete "flotation" data (Figure 19), is the apparently small margin by which an overloaded 4x4 vehicle may fail in deep, dry snow.
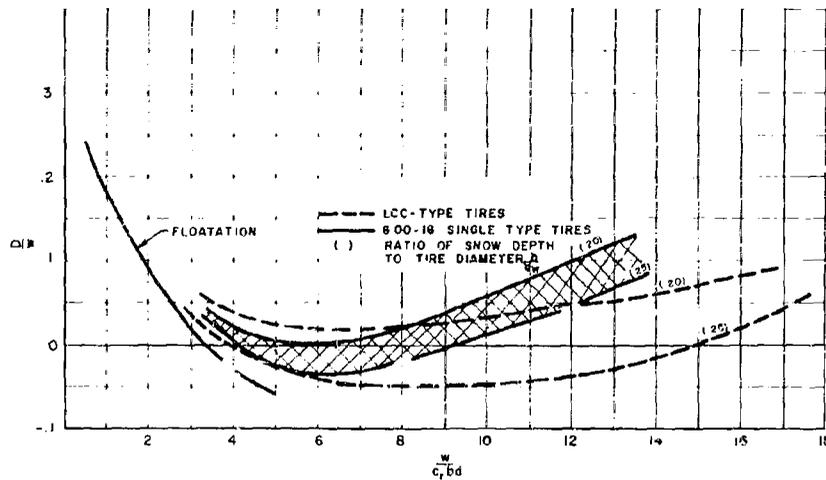
Figure 18. 6.00-16 Single- and LCC-Type Tires for $\dfrac{h}{d_w}$ of From .20 to .25.

21
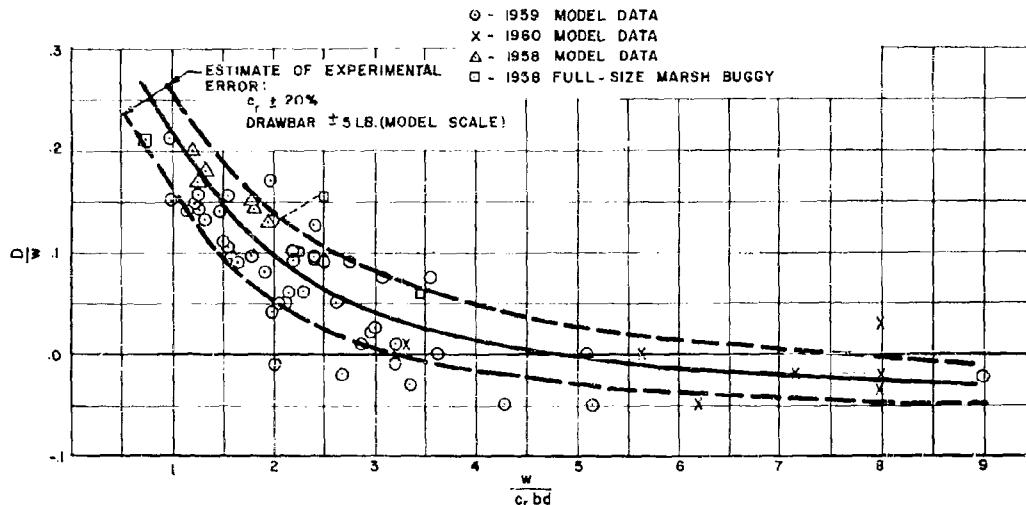
Figure 19. Summary of "Flotation" Data - $\frac{D}{W}$ Versus $\dfrac{W}{c_r bd_w}$.

A few tests were made with the 24-24 rolling-bag tires. Data on these tests are not reported because they were insufficient to determine the performance curves for these tires, even approximately. Moreover, the tests were run in a snow condition that was not typical of those for the rest of the tests. The rolling-bag tests were conducted in moist snow during the final days of the test period when the temperatures ran to above freezing around noontime (testing was stopped at noontime). The tests were made at depths that resulted either in immobilization or in near-immobilization.

The snow built up ("bulldozed") in front of both the front and rear tires. The data, whether reliable or not, indicated a performance inferior to that which was experienced when operating under "flotation" conditions, and thus a stability problem was indicated. The moist snow, which had a noticeably reduced tendency to flow, and the use of wide tires apparently caused a point to be reached beyond which the snow could not flow around the tire without appreciable and costly "bulldozing". This snow condition can result in performance that is considerably reduced from what would otherwise be expected.

"Flotation" Tests - Summary

The results of the 1960 "flotation" tests, together with all of the "flotation" data obtained from the 1959 and 1958 tests, are shown in Figures 19 and 20.

22
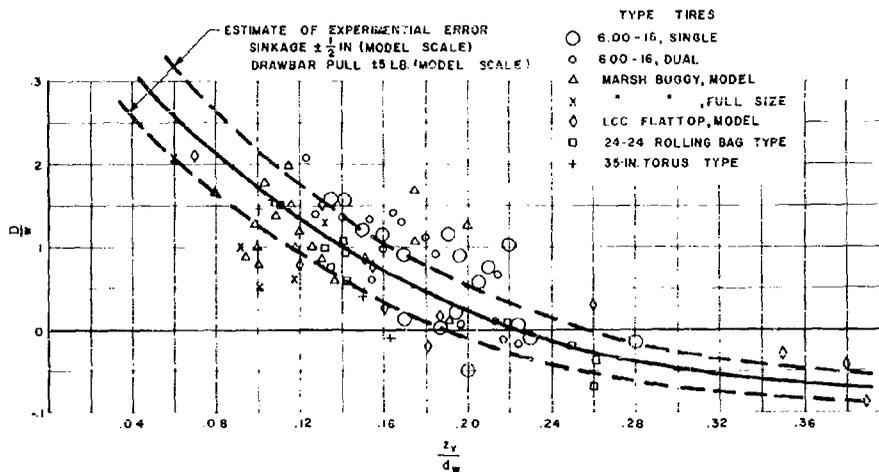
Figure 20. Summary of 82 "Flotation" Tests Conducted Between 1957 and 1960 in Dry, Tree-Belt Snow.

Figure 19 shows dimensionless drawbar pull $\frac{D}{W}$ as a function of the load numeric, $\frac{W}{c_r b d_w}$. Figure 20 is a plot of $\frac{D}{W}$ as a function of dimensionless sinkage, $\frac{z}{d}$. In both figures, an experimental error is approximated and the corresponding band is indicated. Since the tests span three complete snow seasons; since they cover six widely differing tire shapes (with tread, construction, and stiffness differences in addition) and loads from about 200 pounds to 16,000 pounds; and since the analysis and basic factors studied are exceedingly simple, the degree of "collapse" is considered to be excellent. However, there is considerable overall scatter.

There are some minor trends discernible upon close examination of the data already presented. For example, in the $\frac{D}{W}$ versus $\frac{W}{c_r b d_w}$ plot (Figure 19), the torus-type tire and, to a lesser extent, the 24-24 rolling-bag tire do not appear to perform quite as well as the other types of tires. The reason appears to be that, although both are relatively wide, their shapes are such that the full width charged to each in the load numeric is not effective in the snow. As a matter of fact, when the tire is used in a 4x4 configuration, the tire is immobilized before the full width rests on the snow.

There is also a trend for drawbar-pull performance to be slightly better than average at lower values of c_r, and slightly worse at higher values. This is

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confirmed and made reasonable in Figure 20, $\frac{D}{W}$ versus $\frac{z_w}{d_w}$, where the same slight tendency is observable, this time in terms of the performance at a given sinkage, which is often a little better in weaker snows, as expressed by c_1. In these terms, this behavior is entirely reasonable. Figure 20 also shows a trend for the narrower tires to have a higher output than the wide ones at a given sinkage; the 6.00-16 duals are shown to behave definitely as two single tires, despite their close spacing.

Figure 20 is of particular importance because the overall analysis presumes geometric similarity. Accordingly, the prime requisite is for correlation of sinkage results. This figure shows that if a load numeric is developed that completely correlates the sinkages, there still must be some differences remaining in the drawbar performance when plotted on the same numeric.

Some possible sources of scatter, other than experimental error and the relative simplicity (and resulting inexactness) of the correlating numeric, have also been examined. The factors studied were as follows:
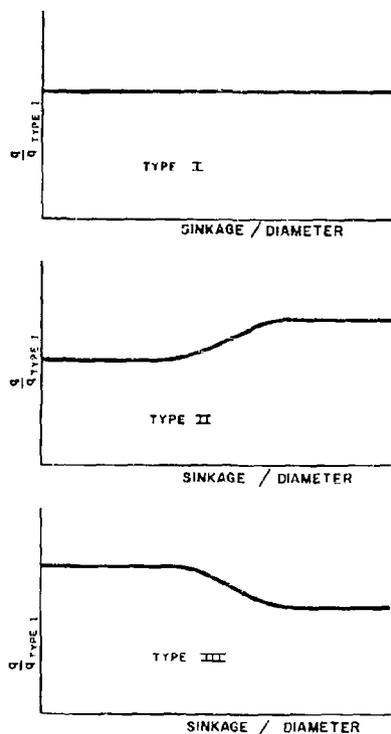
Figure 21.   Snow Types for Data Analysis.

1. Angle of internal friction, ϕ. This is contained in the basic functional equations of performance.

2. Snow type (according to plate pressure-penetration tests). The analysis requires that before complete correlation can be expected, the pressure-penetration profiles must be of the same shape. If they are not, those tests made in different snows cannot be expected to correlate exactly with tests made on the typical type of snow. To determine whether or not this factor had an appreciable effect on the model results, the snow in which each test was run was classified as Type I (typical), Type II, and Type III, according to the approximate shape of the pressure-penetration profiles, as shown in Figure 21.

3. Type of snow failure. It is implicit in the dimensional analysis (in order for the results of two tests to correlate) that not only must the numerics affecting performance be equal but the mechanism and pattern of the snow failure must also be

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similar. Snow fails by a combination of collapse and flow under shear failure. The snow will collapse to a certain maximum density (about 0.4 gm/cm^3), and further failure will then take place by shear and displacement (flow). Varying degrees of collapse and flow failure can be noted from the bonfire pictures; flow can be noted as a bulge along the tire ruts. In a few instances, a tendency toward a brittle-type failure has been noted, as can be observed in the bonfire picture, Figure 22. The failure mechanism and pattern were not always similar. The type of failure in each test, as observed in the bonfire photographs, was estimated on an arbitrary scale of "percent flow failure". Figure 23 shows two bonfire pictures, one that was rated as 0-percent flow failure (i.e., solely collapse failure) and one that was rated as 100-percent flow failure.
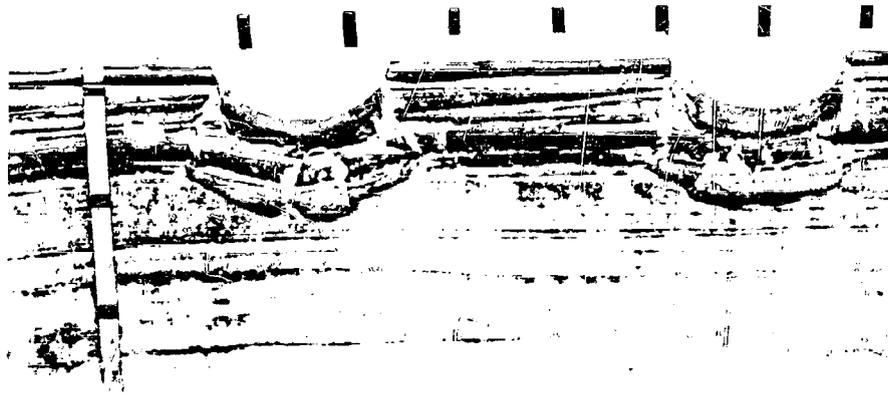
Figure 22. Nakaya Bonfire Picture Showing Brittle-Type Snow Failure. (Condition Indicated by Vertical White Cracks in Lower Part of Disturbed-Snow Zone.)

4. Body force effects. The original complete dimensional analysis included the numeric $\dfrac{W}{\gamma d_w^{3}}$, where γ is density of the snow (Reference 3).

5. Tread-rubber snow friction. It has been assumed that the rubber-to-snow friction, f, is sufficiently large to develop the internal friction, ϕ. Observations made during the test supported this, as evidenced by snow shearing from beneath the tires. The wafers of

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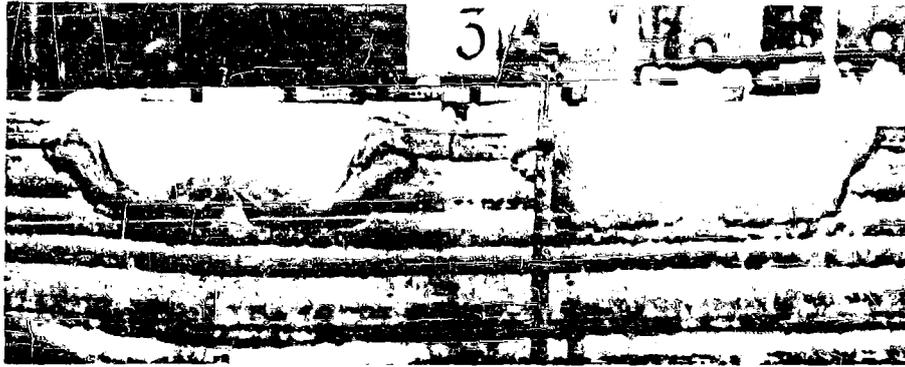
100-PERCENT SNOW FAILURE ESTIMATED

0-PERCENT SNOW FAILURE ESTIMATED

Figure 23. Flow Failure Estimated From Bonfire Pictures.

snow discharged behind the tires shown in Figure 24 indicate there
was no appreciable slippage between the tire surface and snow.
Also, the slip planes, indicating shear failure within the snow,
could be seen in the bonfire pictures (e.g., Figure 25). Although
surface-to-snow slippage could have taken place in some un-
observed instances, no measured values are available and no
quantitative analysis of this factor could be made.

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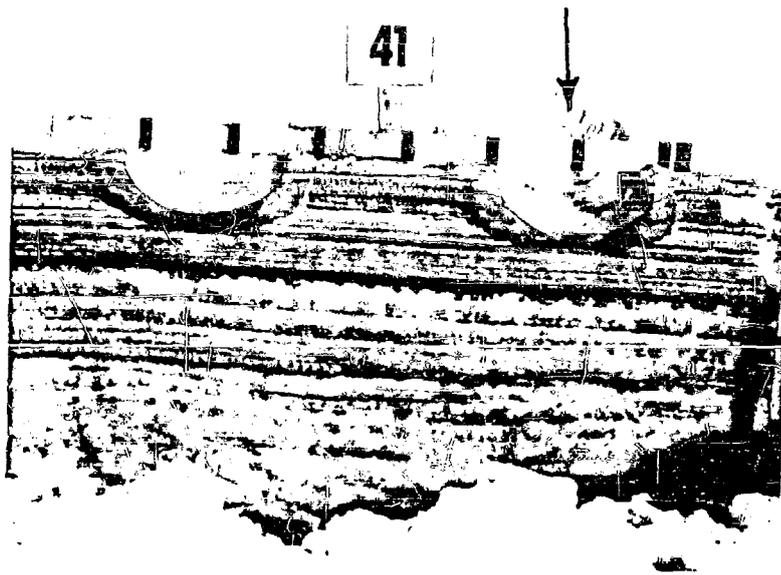
Figure 24. Nakaya Bonfire Picture Showing Wafers of
Snow Sheared From Beneath Tires.
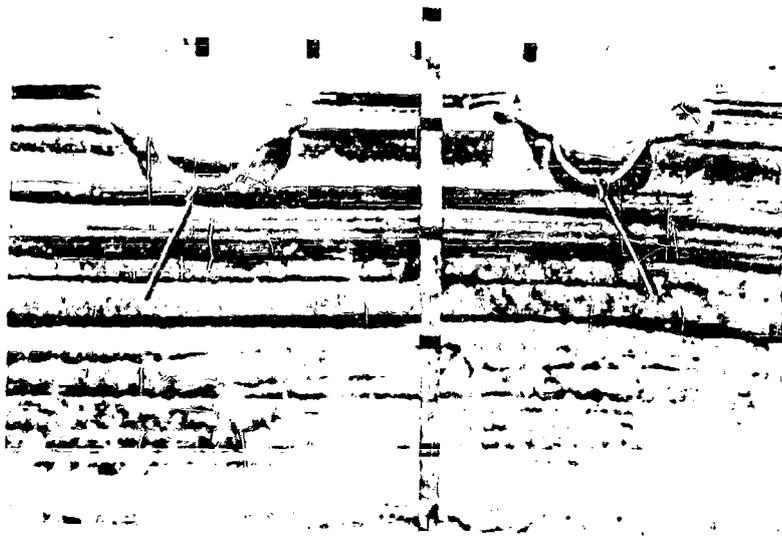
Figure 25. Nakaya Bonfire Picture Showing Slip
Planes.

Snow type (according to plate pressure-penetration curve shape), type of
snow failure (as shown by the bonfire pictures), body forces, and rubber-
snow friction effects all appeared to be negligible as far as explaining the
scatter was concerned. However, if acceptable sinkage correlation is
assumed on the basis of the load numeric $\dfrac{W}{c_r bd_w}$, the drawbar performance,
when keyed to approximate dynamic shearing resistance in terms of $\tan\phi$,
does indicate that variations in this factor may account for some of the
scatter.

Figure 26 indicates that there is a mild qualitative trend for drawbar perform-
ance at a given load numeric to increase with snow shearing resistance ($\tan\phi$)
at the same load numeric and hence
(presumably) at the same sinkage.
This trend, taken with the trend to-
ward increasing performance at a
given loading with increasing snow
"softness" (or decreasing c_r), is not
only reasonable, but, broadly speak-
ing, predictable. It means that
rather than a single curve, there is
a family, most conveniently charac-
terized by using $\tan\phi$ as the para-
meter.* The method of performing
the shear tests was changed for the
1960 tests, and it is apparent that

Figure 26. Drawbar-Pull Data Analy-
sis; Uncorrected Data
From 1959 Tests; Tan ϕ
(Dead-Weight Procedure).

the values obtained were affected by
the test method. Thus, only the 1959
data are considered with $\tan\phi$ values;
the 1960 shear data are discussed in
the next section of this report.

Shear Vane

As has been noted in equation (1), a functional relationship was anticipated
(because of much prior theorizing) between the performance of the vehicle and

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*There is a crude relationship, in general, between dry snow friction, "soft-
ness", and "newness". New-fallen snow tends to have higher friction be-
cause of its greater "roughness". As it metamorphizes, it usually hardens,
and its dynamic friction frequently decreases. This is not a hard and fast
rule; hence, the use of $\tan\phi$ as the sole parameter cannot be expected to
eliminate all scatter from the two causes, although it should help consider-
ably.

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the shearing resistance of the snow, expressed in terms of its angle of internal friction, ϕ . This relationship, however, has not been sufficiently clear in the tests to date; this suggests that the measurement of tan ϕ is somehow in error. The problem is that the vehicle is utilizing the shear strength of a composite material (i.e., several layers of snow) to support and to propel itself simultaneously. Moreover, the material is being altered at the same time that it is being used: first, by collapse and densification of the snow pack because of normal loading; then, by alteration of the snow crystals because of fracture and shear deformation under slippage. The problem, therefore, is not one of measuring a fixed mechanical property of a single material, but rather one of measuring the effective value of the composite material in the state in which it exists at the instant that the vehicle utilizes the property. This is, of course, the same type of problem that is involved in the measurement of other snow (or soil) properties; e.g., the scaled-plate method for determining the relative effective structural cohesion.

Two shear test procedures, essentially, have been used. The first procedure applied the normal pressure to the shear head in dead-weight increments (Figure 27). The postcollapse dynamic shearing resistance was measured for each increment of weight after the resistance had reached a steady value, usually after about a one-quarter revolution of the shear head. Two vane sizes, 25 and 50 square inches, were used. (Vane sizes of 10, 100, and 200 square inches were added for the 1960 tests.) The available torque of the device produced data up to about 3-3/4 p.s.i. The minimum pressure was determined by the tare weight of the device, such that the data from the two vane sizes overlapped for a small portion of the pressure range. Unit shearing resistance was calculated on the assumptions of constant pressure distribution and of neither strain nor strain-rate effects' being involved by $Q = \dfrac{2\pi r^3}{3} \times \tau$

where

Q = torque

r = outside radius of vane

τ = average unit shearing resistance.

A "best" straight line was fitted to the data from both vane sizes, and tan ϕ was determined from the slope of the line (Figure 28). Tests were performed using this procedure from 1956 to 1959. The results are summarized in Tables 3 and 4 of Appendix II. Some of the tests were performed by first disaggregating the snow prior to the test in order to produce loose
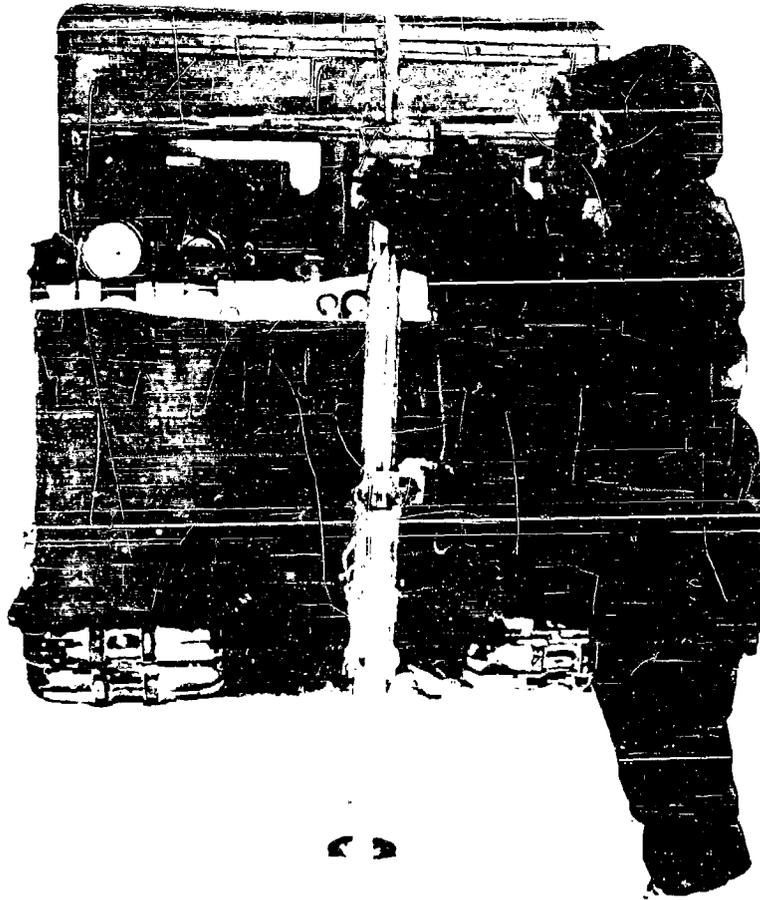
Figure 27.   Shear-Vane Measuring Device Used for 1956-1959
Tests.

snow comparable to what would be left in a rut after the passage of a ve-
hicle.   The friction in disaggregated snow was always slightly less than that
in the virgin snow.

The second procedure, in which new apparatus was employed, was used for
the shear tests conducted in the 1960 tests.   The new apparatus was to be
capable of performing any desired type of shear or penetration test (in-
cluding horizontal shear tests).   However, the static pressure control of the
device was not functioning properly, and the dead-weight test procedure of

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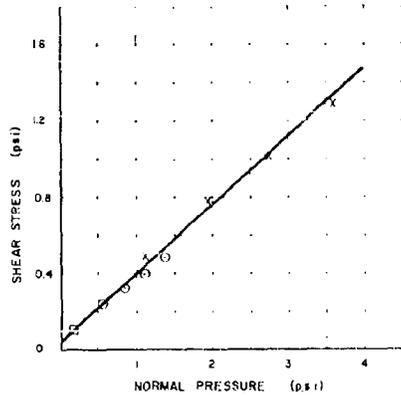
Figure 28. Typical Shear-Vane Curve (Dead-Weight Procedure).

the previous years' tests therefore could not be duplicated. Also, the original apparatus for the first procedure was being used for the snow survey in Canada. For these reasons, the two procedures were not used together for the 1960 model tests as had been intended.

In the second procedure, the shear vane was mounted on a vertical hydraulic ram. The ram was extended at a constant rate while it rotated the vane (Figure 8). The vane was turned by hydraulic motors through the hollow ram shaft. The vane was first brought to the surface of the snow so that the vane was fully imbedded in the snow, but with no normal pressure being applied. Rotation of the vane was started, and then the ram was extended at a constant rate. Normal pressure and unit shearing resistance were plotted on an X-Y recorder. Data determined from this procedure were designated as $\tan\phi_2$. Vane sizes of 10, 25, 50, 100, and 200 square inches were used. Normal pressures were increased until 10 p.s.i. or 300-inch-pounds torque had been reached, whichever occurred first. The rate of penetration was about 1 inch per second, and the angular velocity was about 0.3 revolutions per second.

In the first procedure (the dead-weight), the shear deformation--shear-stress factor (B, Reference 3)--was neither measured nor greatly involved, as only the final steady value of shear, after considerable deformation, was measured. Typical results are shown in Figure 28. The data for the 25- and 50-square-inch vanes generally showed a tendency to be separate straight lines, as in Figure 28. A 200-square-inch vane was added in the 1959 tests; because of torque limitation, data were obtained for only about 1/4 p.s.i. and always agreed closely with data for the other vane sizes. As has been noted in the previous section of this report, the dependence of performance on the angle of internal friction obtained from these tests is weak; i.e., the range of tan ϕ is large while the change of performance is small.

The second procedure (that of measuring at a constant rate of penetration and simultaneous rotation) was intended to include the shear deformation--shear-stress parameter (B, Reference 3). Since the vane was constantly penetrating new layers of snow and since, presumably, the shear surfaces were changing, the shear deformation did not have sufficient time to develop maximum shear stress. The results clearly show this, as some of the tan ϕ_2 values obtained by this method are lower than any obtained by the dead-weight method. (See Appendix II Table 4.) The table shows this comparison for the same vane sizes and for the same range (3-1/2 p.s.i.) of pressure.

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Typical results of the tests made in 1960 using the second procedure are shown in Figure 29, and the entire results are also tabulated in Appendix II. The graphs show a noticeable, but not entirely predictable, effect of the size of the shear vanes. The results obtained with the 10-, 25-, and 50-square-inch vanes vary with respect to each other and to the 100- and 200-square-inch vanes in no fixed relationship; also, the smaller vanes have an overall greater range of values than the 100-square-inch vane. The 100- and 200-square-inch vanes, however, are almost always in close agreement with each other. The irregularity of the smaller vanes may be due to relatively minor dishomogeneities in the snow pack. If so, this suggests that a shear vane should be 100 square inches or larger to avoid unpredictable size effects from this source.
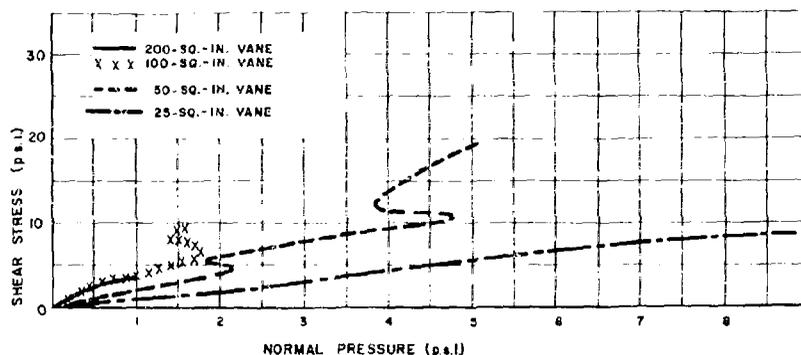
Figure 29.   Typical Shear-Vane Data (Constant Penetration Procedure).

It is still likely that there will be a size effect in the shear measurement. (The 100- and 200-square inch vanes were not always in exact agreement.) The size effect does not appear to be subject to the same scaled-size approach that has been used in the plate penetration tests for the determination of c_r. It has been demonstrated that the scaled bearing plates utilize approximately the same layers of snow as the model tires (Reference 7). Figure 30 is a bonfire picture that shows a plate test and vehicle rut both utilizing the same layers of snow. However, the shear cone developed under the shear head probably varies in size and depth according to the vane size. Thus, at a given penetration, it is shearing through different snow stratifications according to the depth of the shear cone. It is, therefore, possible that the shear head should be about equal to the minimum dimension of the tire contact area. (This, of course, would not be desirable for large tires because of the difficulty of making the measurement with such a large shear head.) More recent tests in sand, when using the second procedure, have also indicated that measured tan ϕ is sensitive to rate of penetration. If this is
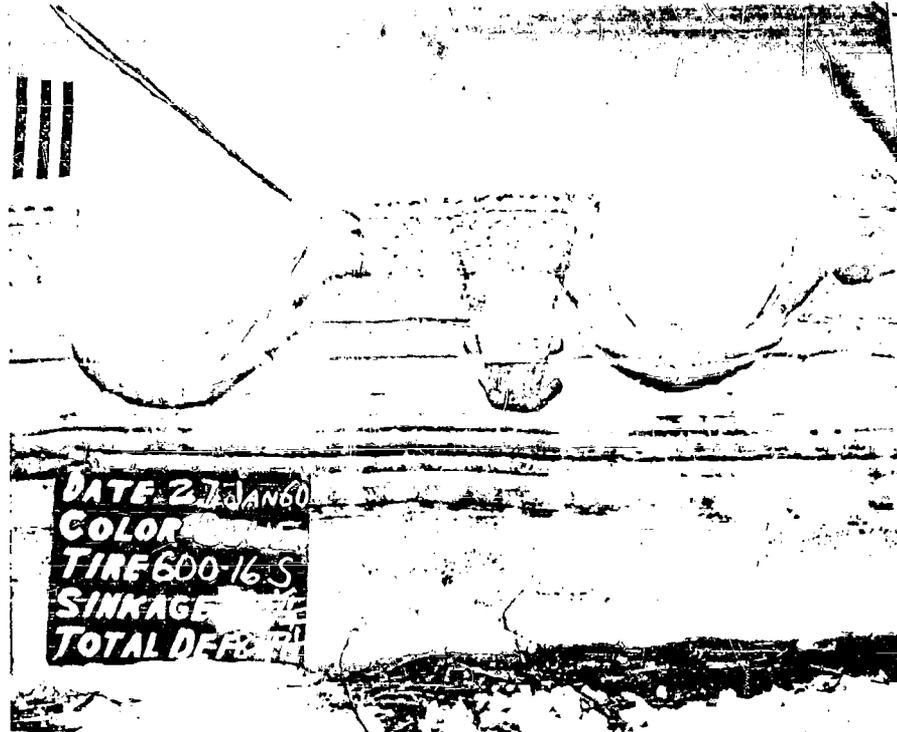
Figure 30.   Bonfire Picture Showing Both Plate and Tire
Utilizing Same Snow Layers.

true in snow also, some thought and experimental study must be given to the
problem of proper rates for correlation.   The rates may not want to be the
same for heads of different sizes.

The shear curves, of which Figure 29 is typical, are nonlinear and have
frequent sudden changes of slope.   This probably results when the shearing
plane extends through stratifications of hard snow (crust layers).   The struc-
tural cohesion of these crusts is utilized; when broken up, the material be-
comes again solely frictional.

The problem becomes even more complex when it is considered that neither
the pressure distribution under the tires nor that under the shear vanes is
constant.   The shear curves are appreciably nonlinear.   Therefore, since
the vehicle is operating over a range of normal pressures, ϕ must be
expressed as an average for the range of pressures involved; to be com-
pletely accurate, ϕ must be weighted according to the actual pressure
distribution under the tires and the vanes.   However, the 1960 method
appears to be basically adequate, although it must be developed and checked
further.

Since sand and snow are both frictional granular materials and since they fail in a similar manner (i.e., by collapse and flow), it is probable that there would be a correspondence between the performance of vehicles in snow and in sand. In Reference 9, it is shown that if the strength of sands in terms of c_r is determined from the same standard as that of snow (rather than to a scale where c_r sand = 1 is equivalent to c_r snow = 16.5), the drawbar-pull performance curves for tires in sand and in snow are remarkably similar in shape (see Figure 31). The difference in values may be assigned to the relatively large and consistent difference in tan ϕ (by the first procedure, about 0.4 for snow and 0.7 for sand).

It would be a great convenience if "ground-supported" snow performance could be determined from scaled-depth tests in sand. It seems possible that this can be done. There are sufficient scaled-depth snow data in this report to check the results which could be obtained on some pilot runs in sand.

LOAD NUMERIC - $\frac{w}{c_r bd}$

(ALL REFERRED TO TYPE I SNOW CURVE)

Figure 31. Comparison of Draw-bar-Pull Performance Tests Conducted in Sand and Snow.

Snow Survey

When considered with proper snow values, the data and methods of this report will permit the solution of a wheeled off-road-snow-vehicle design problem in terms of its most important element, namely performance. The snow data of most interest would probably be those for the worst condition that could be expected to occur for a certain number of days a year in the "difficult" snow areas where the vehicle could be expected to operate.

The "difficult" snow zone (excluding mountain areas) is a belt extending across the North American continent that is below the tree line and above the freeze-thaw zone. A similar belt extends across the eastern hemisphere. Data on the Houghton, Michigan, area are available for the period 1958 to 1960. A pilot snow survey in terms of the snow strength parameters developed

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by the U. S. Army Transportation Research Command in this research was initiated in Canada in 1960 by a traveling team. The results of this limited survey are presented in Appendix II. More extensive snow depth information is available from a survey conducted by the Canadian Government during the period 1946 to 1950 (Reference 9).

EVALUATION

The scale-model performance data presented herein can be used as a design basis for 4x4 wheeled vehicles having equal weight distribution when the vehicles are intended for operation in typical "difficult" below-the-tree-line snow.

The data for the "ground-supported" performance cover the range for more-or-less normal tire proportions but do not cover the complete range of tire width-to-diameter ratios.

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APPENDIX I

SUMMARY OF TIRE DATA

Date	Tire	Gross Weight (lb.)	$\dfrac{D}{W}$	$\dfrac{z_w}{d_w}$	$\dfrac{h}{d_w}$	c_r	$\dfrac{W}{c_r d_w^2}$	$\dfrac{W}{c_r b d_w}$
1960 28 Jan	6.00-16, S	195	.10	.22	•	.20	1.3	5.5
"	"	195	.11	.19	•	.22	1.2	4.95
"	"	495	.02	.28	•	.34	1.9	2.0
1 Feb	Goer, Full-Size	34,775**	.06	.15	.21	1.63	4.08	-
"	"	"	.09	.14	.18	1.52	4.32	-
"	"	"	0	-	.27	1.52	"	-
"	"	62,450	.10	.16	.22	1.98	5.9	-
"	"	"	.13	.15	.20	"	"	-
10 Feb	6.00-16, Single	195	.12	.15	•	.32	.8	3.4
"	"	295	.115	.16	•	.49	.8	3.35
"	"	395	.01	.17	•	.66	.8	3.3
"	"	495	-.05	.20	•	.44	1.2	6.2
"	"	595	-.20	.22	•	.36	2.1	8.95
26 Feb	LCC, Model	544	-.045	.38	•	.07	8.7	21.5
"	"	644	-.09	.39	•	.07	10.2	25.5
29 Feb	"	544	.03	.26	•	.19	3.2	8.0
4 Mar	"	"	-.03	.35	•	.08	7.6	19.0
8 Mar	24-24 Bag	666	-.07	.26	•	.10	11.3	11.5
"	"	566	-.035	.26	•	.12	8.0	8.00
"	"	466	-.02	.25	•	.11	7.2	7.15
"	"	366	0	.22	•	.11	5.6	5.65
10 Mar	LCC, Model	1,004	.17	.09	.13	.87	1.3	-
"	"	"	.05	.13	.19	"	"	-
"	"	"	0	.22	.29	"	"	-
"	"	1,804	.12	.07	.13	2.75	.74	-
"	"	"	.13	.07	.10	"	"	-
"	"	"	.04	.10	.14	"	"	-
10 Mar	6.00-16, Single	2,055	.10	-	.25	.78	3.4	-
"	"	"	.06	-	.18	1.57	1.7	-
"	"	"	.16	-	.13	1.58	1.7	-
"	"	855	.23	-	.08	1.26	.9	-
"	"	"	.01	-	.19	1.25	.9	-
"	"	"	.02	.	.22	1.09	1.0	-
11 Mar	LCC, Model	2,604	.38	.03	.02	3.40	.87	-
"	"	"	.24	.07	.09	"	"	-
"	"	"	.20	.08	.11	"	"	-
"	"	"	.14	.09	.14	"	"	-
"	"	3,404	.16	-	.13	2.75	1.4	-
"	"	"	.12	-	.15	1.6	2.4	-
"	"	"	.03	-	.22	1.2	3.2	-

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Date	Tire	Gross Weight (lb.)	$\frac{D}{W}$	$\frac{\delta_w}{l_w}$	$\frac{h}{d_w}$	c_r	$\frac{W}{c_r d_w^2}$	$\frac{W}{c_r b d_w}$
14 Mar	LCC, Model	2,604	.7	.10	.17	1.4	2.1	-
"	"	"	-.05	.16	.24	1.2	2.4	-
"	"	"	-.07	.20	.29	1.2	2.4	-
15 Mar	6.00-16, Single	3,255	.20	-	.15	1.4	3.0	-
"	"	"	.16	-	.21	1.03	4.1	-
"	"	"	.02	-	.25	1.16	3.6	-
16 Mar	LCC, Model	6,362	.18	-	.19	1.5	4.8	-
"	"	"	.03	-	.22	1.2	5.9	-
"	"	"	0	-	.23	"	"	-
"	"	"	.1	-	.18	1.5	4.8	-
1956 Recapitulation	LCC, Model	1,060	.26	.03	.10	1.40	.8	-
"	"	"	.22	.05	.13	"	"	-
"	"	"	.16	.07	.17	"	"	-
"	"	"	.10	.08	.20	"	"	-
"	"	"	.07	.10	.24	"	"	-
"	"	"	0	.11	.27	"	"	-
"	"	2,500	-.02	.13	.25	"	1.9	-
"	"	"	-.01	.11	.24	"	"	-
"	"	"	.01	.10	.22	"	"	-
"	"	"	.22	.06	.13	"	"	-
"	"	3,940	0	.21	.47	.70	8.0	-
"	"	"	.05	.17	.37	"	"	-
"	"	"	.07	.15	.34	"	"	-
"	"	"	.12	.10	.24	"	"	-
"	"	"	.14	.09	.20	"	"	-
"	"	"	.19	.05	.13	"	"	-
"	"	"	.30	.04	.10	1.40	3.1	-
"	"	"	.22	.07	.13	"	"	-
"	"	"	.17	.08	.15	"	"	-
"	"	"	.09	.10	.18	"	"	-
"	"	"	0	.12	.23	"	"	-
"	LCC, Full-Size	58,700	.06	.12	.21	2.8	1.5	-
"	"	"	.07	.10	.20	"	"	-
"	"	"	.01	"	.23	"	"	-
"	"	"	-.02	.16	.25	"	"	-
"	"	"	.10	.12	.21	1.9	2.2	-
"	"	"	.06	.14	.25	"	"	-
"	"	"	-.02	.16	.29	"	"	-
"	7.00-16	3,940	.06	.20	.25	1.4	3.2	-
"	"	2,500	0	-	"	1.4	2.0	-

*Flotation test; snow sufficiently deep to avoid ground support.
**Unequal weight distribution: 24,000 lb., front; 12,000 lb., rear.

APPENDIX II

SNOW SURVEY RESULTS

The data that are presented in this appendix show the level of snow values that can be expected to occur for a given number of days a winter in "difficult", subarctic, below-the-tree-line snow regions; however, because of the limited number of locations sampled and the limited number of tests performed, the data are tentative and do not describe accurately the geographical distribution of values.

The "difficult" snow region known as the Northern Forest Region is a belt extending across the North American continent. This is the principal region which presents "difficult" snow conditions for the passage of vehicles. (See Figure 32.) A similar belt extends across the eastern hemisphere. While
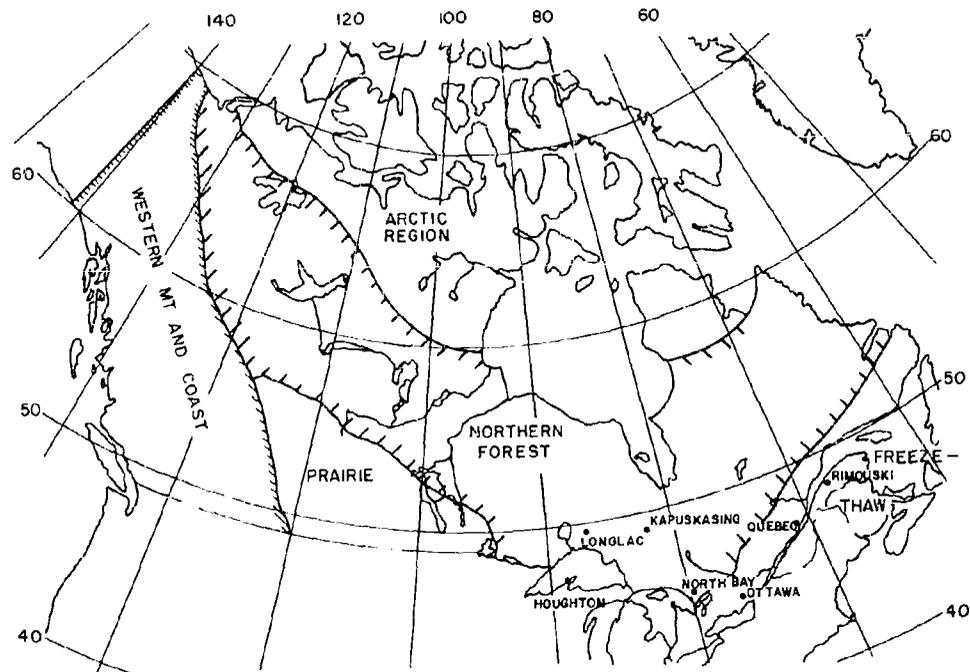
Figure 32. Test Locations and Snow Regions.

mountainous areas of "difficult" snow exist, they are of less areal extent than the Northern Forest Region. Testing was not performed in the permanent snow regions of the Greenland Ice Cap and Antarctica; only the sub-arctic, below-the-tree-line region was included in the survey. The survey

of the Northern Forest Region, other than Houghton, was undertaken in the winter of 1959-1960 by a mobile snow survey team.

Measurements were made by methods discussed in Test Procedures and Results in this report and in Reference 9. All measurements were made in profile increments of 2-1/2 inches. (See Figure 33.) All of the data were recorded on data sheets in digital form.

HOUGHTON, MICHIGAN; 13 FEBRUARY 1959; SNOW DEPTH: 32 IN.

HOUGHTON, MICHIGAN; 10 FEBRUARY 1959; SNOW DEPTH: $35\frac{1}{2}$ IN.
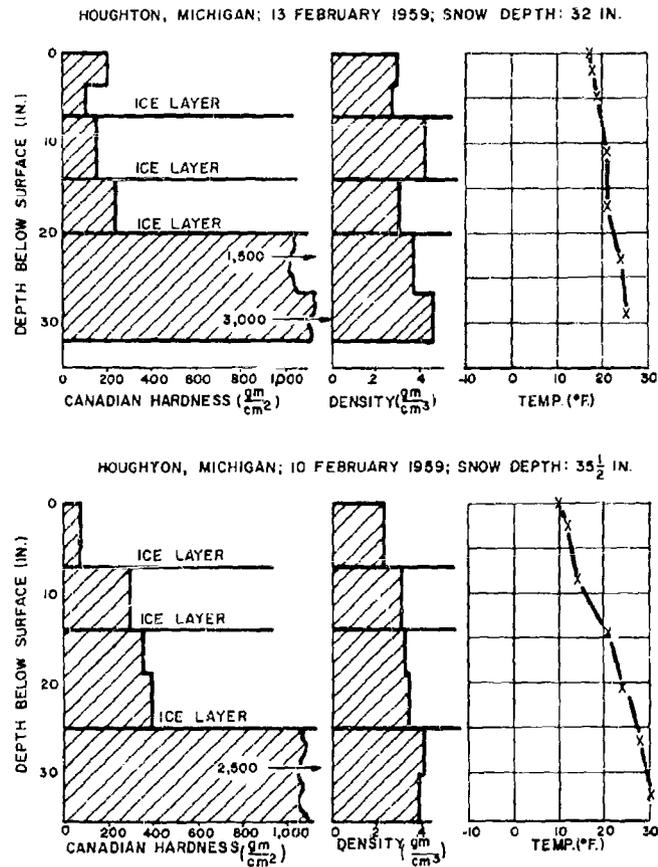
Figure 33. Typical Profile Measurements in Snow.

TEST LOCATIONS

The Northern Forest Region is indicated on the map shown in Figure 32. Tests were conducted at various locations having a variety of terrain and surface features, and of failure characteristics, all of which have been assigned the following code numbers for identification:

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Locations	Code Number
Quebec, Quebec (Val Cartier)	1
Ottawa, Ontario	2
Kapuskasing, Ontario	3
Longlac, Ontario	4
North Bay, Ontario	5
Ramouski, Quebec	7
Houghton, Michigan	10

Terrain Features	
Open level field, sparse vegetation	1
Level field, sparse vegetation, sheltered by surrounding woods	2
Woods or woods trails	3
Frozen lake	4

Surface Features	
Smooth new snow	1
Smooth crust	2
Scalloped or etched drifts	3

Snow Failure Characteristics	
Collapse	1
Brittle	2
Flow	3

Collapse failure is failure which results from collapse and densification of the snow particles. (See Figure 34.) When the snow is sufficiently bonded to form a cohesive solid, rather than a collection of unbonded particles, the failure that occurs by snow's breaking into pieces is termed brittle. (See Figure 22.) Flow failure takes place when the snow fails by shear failure and flow, rather than by densification. (See Figure 35.) Typically, at least two types of failure can be noted in the various layers of disturbed snow. Generally, the failure will start as primarily collapse at small sinkages. As the sinkage progresses, the density increases until a density of about 0.4 gm/cm^3 is reached, and thereafter, further failure will proceed by flow. Where two types of failure were noted, the code number for the dominant type of failure is shown first on the graphs.

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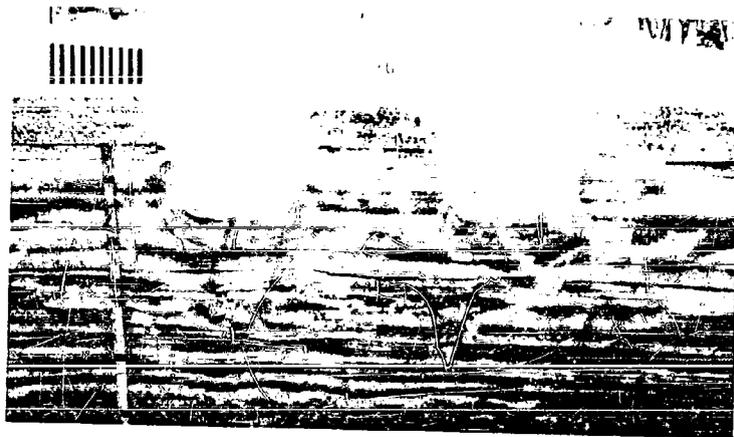
Figure 34. Bonfire Picture Showing Collapse-
Type Snow Failure.
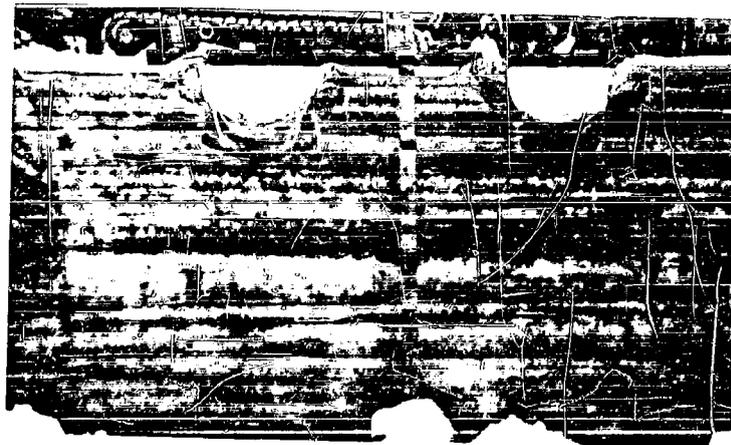
Figure 35. Bonfire Picture Showing Partial-
Flow-Type Snow Failure.

PLATE PENETRATION DATA

The snow quantities of greatest influence on vehicle performance are snow depth (h) and the relative effective value of the structural cohesion (c_r). The method of measuring c_r for the scale model tests has been to measure the pressure-penetration profile with round plates. (See Figure 36.)
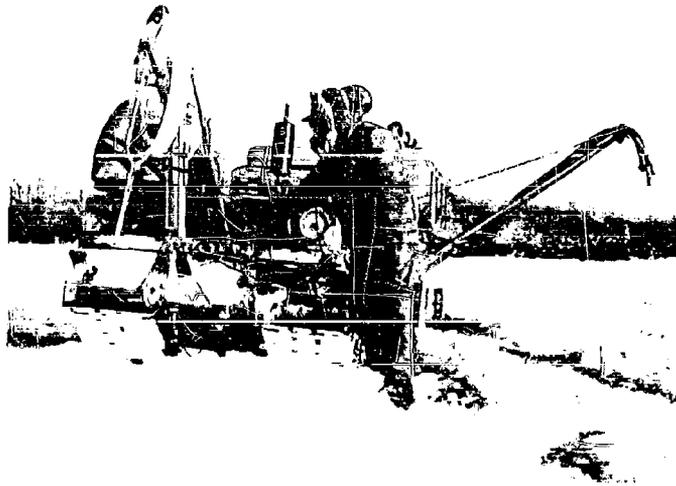
Figure 36.   Plate-Penetration Test Apparatus.

Results of the plate penetration tests are summarized in Table 3.   (See page 47.)   The areal homogeneity of the snow was generally good; only a few tests were necessary to describe an area.   Figure 11 shows three typical replications made within a distance of 5 feet.   The relative strength value, c_r, was determined for plate penetrations of 2 × plate diameter, or, where the snow depth was insufficient for this, within one plate diameter of the ground.   The plate was presumed to become "ground supported" when it approached within one diameter of the ground, which is approximately in accordance with the data shown in Table 2 and the photograph shown in Figure 37.

The scale-model tests showed that tires become "ground supported" before immobilization occurs if the snow depth is less than 0.3 tire diameter, or, in terms of the scaled plates, 3 × plate diameter.   The vehicle can become immobilized at lesser depths, but the performance will be governed by "ground-supported" data; the vehicle will not become immobilized for any vehicle weight or snow strength if the snow depth is less than about 0.2× tire diameter.   For tire diameters of 90 inches or less, snow depths will generally be more than enough to permit "flotation" immobilization.   However, for the 120-inch-diameter tires, the snow depth will quite often be insufficient to cause immobilization before "ground support" occurs, and vehicle performance is then determined from "ground-supported" data. For complete generality, the expected snow strength should be known for snow depths less than the depths required for "flotation".   The performance

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TABLE 2

DEPTHS OF PLATE AND POLECAT SINKAGES AND DEFORMED SNOW (HOUGHTON)

Date	FLAT 3-Inch Diameter Sinkage (In.)	Def. Snow (In.)	6-Inch Diameter Sinkage (In.)	Def. Snow (In.)	9-Inch Diameter Sinkage (In.)	Def. Snow (In.)	12-Inch Diameter Sinkage (In.)	Def. Snow (In.)	POLECAT Sinkage (In.)	Def. Snow (In.)	Snow Depth (h) (In.)
1959											
13 Feb	7.0	1.0	-	-	-	-	-	-	-	-	-
16 Feb	6.0	1.2	-	-	-	-	-	-	-	-	-
25 Feb	8.0	2.9	-	-	-	-	-	-	-	-	-
26 Feb	7.0	2.9	-	-	-	-	-	-	-	-	-
1960											
27 Jan	7.0	2.2	-	-	-	-	-	-	-	-	-
4 Feb	8.4	3.4	12.5	5.5	3.0	3.0	7.8	7.7	-	-	-
8 Feb	6.5	4.0	11.0	5.5	13.0	6.7*	11.5	9.0*	7.0	7.0	26
9 Feb	5.4	3.0	10.5	4.5	12.5	1.8*	12.0	6.0*	8.5	12.0*	21
16 Feb	6.0	1.9	10.5	7.0*	14.0	3.2*	14.0	5.0*	9.0	9.0*	18
21 Feb	7.5	5.8	12.0	11.0	17.5	7.2*	15.5	9.0*	12.0	7.5*	18
26 Feb	10.5	2.9							10.0	8.0	22
1 Mar	6.9	2.8	12.5	5.5	19.5	13.2	22.5	12.5	12.5	18.0	25
Average Depth Deformed**		3.2		6.4		9.6		10.1			43

*Ground support indicated in bonfire photograph.
**Data excluded where ground support is indicated.
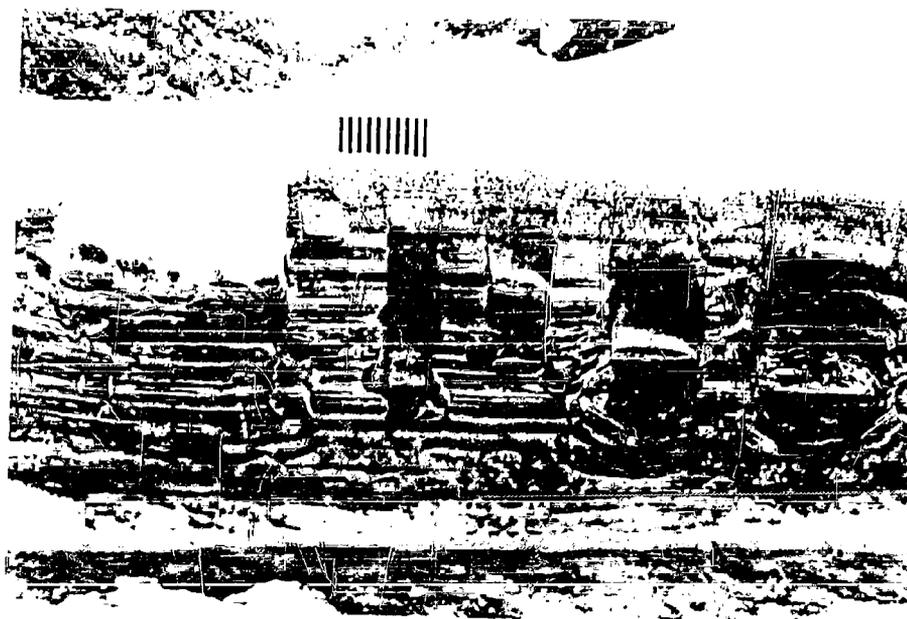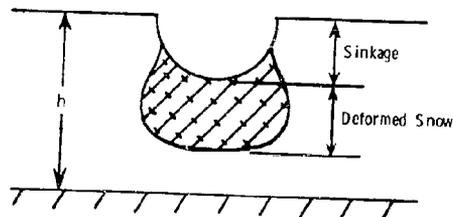
Figure 37. Plate and Polecat Sinkages. (Left to Right: Polecat Track, Rear Unit; 3-, 3.4-, 6-, 9-, and 12-Inch Diameter Plates.)

would then be based upon the strength value and the depth. The present data are statistically insufficient for this. However, since the snow has a general tendency to increase in strength with depth (Figure 38), the strength of snow at less than "flotation" immobilization depth can be approximated by assuming this depth-proportional relationship. Figure 39 shows the strength distribution of the tests made in snow of sufficient depth to cause "flotation" immobilization (3 × plate diameter). Because of the limited survey data, the data for tests of snow of slightly lesser depth have been included by first determining c_r up to the plate penetration of one diameter from the ground. Then, the value of c_r was increased to that of an equivalent snow pack of "flotation" immobilization depth by assuming the usual linear increase of strength with depth. Also, data from all of the test locations have been lumped together, regardless of the number of tests performed at each site. Data for all the different terrain features

Figure 38. Increase of Snow Strength With
Depth (Typical Data).
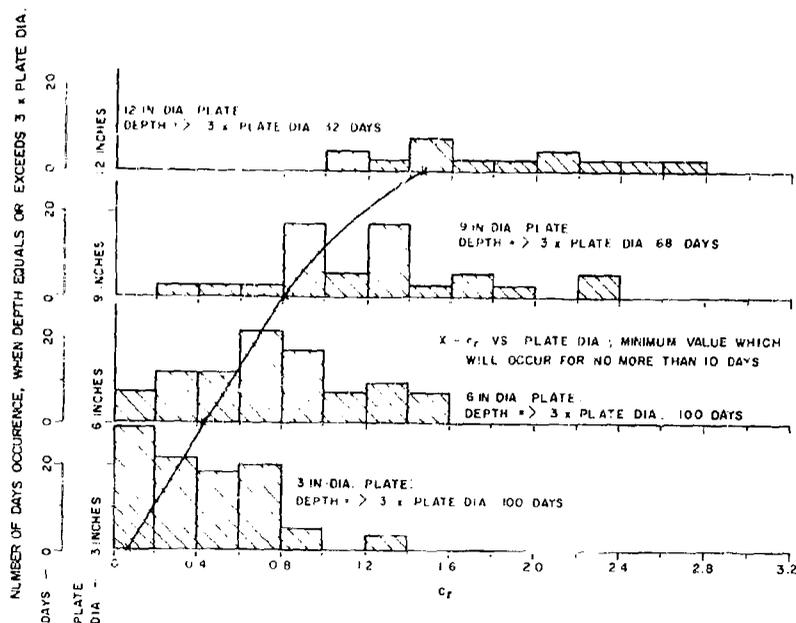
Figure 39. Distribution of Snow Strength for 100-Day
Season of "Difficult" Snow (From Preliminary
Survey of Tree-Belt Snow Areas, 1958-1960).

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are also lumped together in Figure 39, although the preponderant number of observations were made in the sheltered fields and woods or woods trails, which are where the most "difficult" snow occurs. (See Figure 40.)
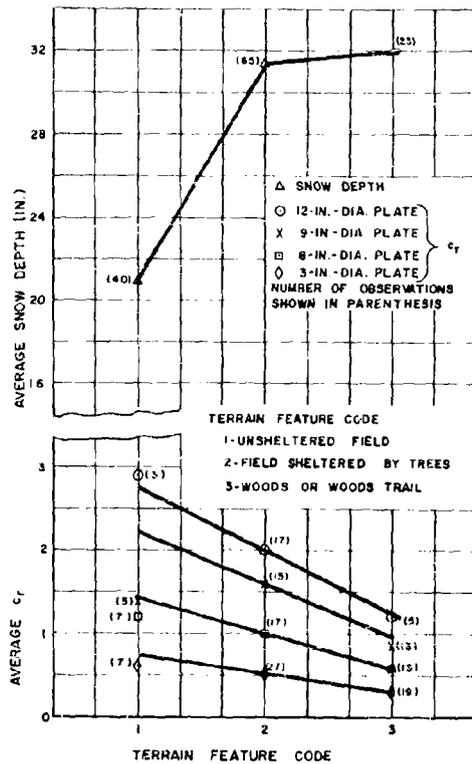

Figure 40. Variation of Snow Properties With Terrain Features.

The percentages shown in Figure 39 can be interpreted in terms of number of days by tentatively assuming a "difficult" snow season to be a 100-day period between 10 December and 18 March. This period will approximate the "difficult" snow season. For the 12-inch plate, snow depths sufficient for "flotation" immobilization occurred for only about 32 percent (or 32 days) of this period and for the 9-inch plate, about 68 percent (or 68 days). For the 6- and 3-inch plates, the snow depth was sufficient for "flotation" immobilization almost 100 percent of the time.

While considerable variations occur, the data indicate that the structural profile of the typical snow condition is as described by Figure 9. An important aspect of the plate data is the characteristic of strength increasing with depth. Thus, larger vehicles, which can tolerate more sinkage without becoming immobilized, do not need to have the same low ground pressure required for smaller vehicles. Not only snow but most natural terrains exhibit this characteristic; e.g., sand (Reference 9). The curve in Figure 38, which shows c_r versus plate size for given snow packs, is typical of the generally linear strength increase with depth of snow.

The only observed marked departure from this general tendency of strength increase with depth occurred at Kapuskasing, Ontario, on 21 January 1960. (See Table 3.) The snow strength was very weak and nearly constant with depth. This was a snow pack that had accumulated quickly and without time for the lower layers to undergo the usual aging process. This condition probably existed for less than a week. The snow was so weak in the lower layers that a large vehicle having 120-inch-diameter tires and the lightest possible weight would be immobilized as a "flotation" vehicle. However,

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TABLE 3
PLATE PENETRATION DATA

Date	Snow Depth (in.)	c_r Plate Diameter (In.)						Location	Temp. Texture (2)	Tan ϕ_1 (3)	100-Sq-In. Vane Tan ϕ_2 (4)	Polecat Sinkage (In.) (5)
		12	12 (1)	9	9 (1)	6	3					
1958												
6 Feb	30	1.8	2.2	-	-	-	.15	Houghton	2	-	-	-
11 Feb	27	1.2	1.6	-	-	.8	.42	"	"	-	-	-
12 Feb	31	1.3	1.5	-	-	-	.55	"	"	-	-	-
13 Feb	28	1.3	1.7	-	-	.7	.67	"	"	-	-	-
17 Feb	26	1.6	2.2	-	-	.7	.55	"	"	-	-	-
19 Feb	28	1.4	1.8	-	-	.8	.58	"	"	-	-	-
24 Feb	26	6.0	8.3	-	-	-	-	"	"	-	-	-
1959												
26 Jan	26	2.8	3.9	1.9	NA	1.2	-	"	1	-	-	-
28 Jan	28	-	-	-	-	-	.63	"	"	-	-	-
29 Jan	31	4.0	4.6	2.3	NA	1.6	.82	"	"	-	-	-
2 Feb	33	2.3	2.5	1.6	NA	1.3	.74	"	2	-	-	-
3 Feb	35	2.4	NA	1.6	NA	1.0	.38	"	"	-	-	-
4 Feb	37	1.9	NA	1.2	NA	.9	.51	"	"	-	-	-
5 Feb	33	2.1	2.3	1.2	NA	.9	.60	"	"	-	-	-
6 Feb	33	2.6	2.8	1.2	NA	.9	-	"	"	-	-	-
9 Feb	34	2.1	2.2	.7	NA	-	.40	"	"	.48	-	-
10 Feb	36	-	-	-	-	-	.55	"	"	-	-	-
11 Feb	35	-	-	-	-	-	.69	"	"	-	-	-
12 Feb	34	-	-	-	-	-	.64	"	"	-	-	-
13 Feb	32	-	-	-	-	-	.61	"	"	.39	-	-
16 Feb	30	1.4	1.7	1.4	NA	1.2	1.3	"	"	.50	-	-
19 Feb	30	-	-	-	-	-	.59	"	"	-	-	-
20 Feb	30	-	-	-	-	-	.67	"	"	.76	-	-
24 Feb	23	*	*	1.7	2.0	1.2	.42	"	3	.40	-	-
25 Feb	28	1.6	2.1	1.2	NA	.7	.38	"	"	.36	-	-
26 Feb	29	-	-	-	-	-	.37	"	"	.39	-	-
2 Mar	33	1.5	1.6	1.0	NA	.6	.40	"	"	-	-	-
1960												
25 Jan	18	*	*	*	*	.5	.17	"	1	-	.45	-
28 Jan	25	*	-	-	*	-	.23	"	2	-	.43	-
1 Feb	14	*	*	*	*	-	.87	"	1	-	.35	-
2 Feb	15.5	*	*	*	*	3.0	.80	"	"	-	.43	-
3 Feb	13.5	*	*	*	*	*	1.22	"	"	-	-	4
4 Feb	25	*	*	2.3	NA	1.6	.64	"	2	-	.38	7
8 Feb	25	*	*	2.6	2.8	1.4	.38	"	"	-	-	8.5
9 Feb	24	*	*	.4	4.5	1.4	.80	"	"	-	.45	9
10 Feb	22	*	*	2.8	NA	1.4	.55	"	"	-	.45	-
18 Feb	20	*	*	1.1	1.5	.6	.19	"	3	-	-	12
19 Feb	19	*	*	1.0	1.4	.4	.17	"	"	-	.40	-

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Table 3 - contd.

Date	Snow Depth (in.)	c_r Plate Diameter (in.) 12	12 (1)	9	9 (1)	6	3	Location	Terrain Feature (2)	Tan ϕ_1 (3)	100-Sq.-In. Vane Tan ϕ_2 (4)	Polecat Sinkage (In.) (5)
1960												
21 Feb	26	7.4	3.1	1.2	NA	-	.40	Houghton	2	-	25	16
26 Feb	19	-	-	-	-	-	.07	"	3	-	.45	-
29 Feb	39	1.21	NA	.90	NA	6	.19	"	"	-	.48	-
4 Mar	45	-	-	-	-	-	08	"	"	-	.35	-
7 Mar	39	1.4	NA	1.20	NA	.8	.16	"	"	-	.30	-
4 Jan	22	*	*	.8	1.0	4	.05	Quebec	2	.37	-	11.5
6 Jan	22	*	*	.5	.6	.2	.03	.	3	-	-	15
29 Feb	36	1.4	NA	97	NA	.85	.38	"	2	-	-	11
1 Mar	38	1.6	NA	83	NA	.80	.23	"	3	.53	-	16
11 Jan	12	*	*	*	*	*	.70	Ottawa	3	.33	-	7.5
18 Jan	21	*	*	1.2	1.5	8	35	Kapuskasing	1	-	-	7
19 Jan	18	*	*	6	.9	4	.14	"	"	-	-	-
21 Jan	27	.25	.33	30	NA	.25	25	"	3	33	-	17
7 Mar	28	1.9	2.4	90	NA	1.0	65	"	1	.58	-	12
9 Mar	36	1.0	NA	53	NA	65	15	"	3	.53	-	14
25 Jan	18	*	*	26	.39	.20	13	Longlac	4	.43	-	10
26 Jan	23.5	*	*	26	.30	15	.10	Longlac	3	33	-	-
14 Mar	23.5	*	*	45	52	30	14	"	"	.52	-	14
18 Feb	42	1.0	NA	82	NA	60	20	Ramouski	2	25	-	17

- No test performed
* Depth insufficient for test
(1) Value presumed for snow pack of sufficient depth to avoid ground support.
(2) Terrain Feature: 1 Open level field, sparse vegetation. 2 Open level field, sparse vegetation, sheltered by surrounding woods. 3 Woods, or woods trail. 4 Frozen lake.
(3) Tan ϕ_1, by dead weight loading test method, average of 25- and 50-sq.-in. vanes.
(4) Tan ϕ_2, by simultaneous rotation and penetration method, 100-sq.-in. vane to 2 p.s.i. normal pressure.
(5) The Polecat is an articulated vehicle with Weasel (M29C) tracks and suspension. The front unit weighed about 4,400 pounds, the rear 6,100 pounds. Each of the four tracks has a nominal contact area of 20 x 78 inches, resulting in a nominal unit ground pressure of 1.94 p.s.i. on the rear unit.

such a vehicle, since it is considerably overloaded for "flotation", would be almost capable of retaining mobility with "ground support" because the snow depth was less than the "flotation" immobilization depth. Smaller diameter wheels in this snow would fail in both "flotation" and "ground-supported" operation. Snow packs of this type can be expected only in the early-season period, when heavy snowfalls result in a rapid accumulation of depth without time for appreciable aging of the lower layers.

In general, the snow is deeper and softer in the sheltered and woods areas. This is shown in Figure 40. Additional observations of snow depths are included for days not included in Table 3--days for which no plate tests were made. All of the depth observations were made near Houghton, from 1955 to 1960, except those made in Canada and shown in Table 3.

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SHEAR VANE DATA

Of the two different test procedures described earlier in this report for use in shear vane tests, the dead-weight procedure was used for the 1957, 1958, and 1959 tests at Houghton, Michigan, and for the 1960 tests in Canada. The second procedure, that of measuring at a constant rate of penetration and simultaneous rotation, was used only at Houghton, Michigan, during the 1960 scale-model tests.

The results of the shear vane tests are shown in Table 3 and more completely in Table 4. (See page 50.) Table 4 is a tabulation of the shear vane tests made during a 5-year period and shows the range of values obtained by the two test procedures. (Typical test results of the first procedure are shown in Figure 28, and those of the second procedure in Figure 29.)

Attempts to correlate the friction data with scale-model test results indicated that data determined from using the second procedure (constant rate of penetration and simultaneous rotation) were more closely reflected in the vehicle performance than data from the first procedure (the dead-weight). Also, the data obtained with the 100-square-inch vane corresponded closer to vehicle performance than the data obtained from the smaller vanes. Tan ϕ could not be determined from the 200-square-inch-vane because the torque limitation of the devices limited the normal pressures that could be used. The 200-square-inch-vane data, however, nearly always agreed more closely with the 100-square-inch-vane data than with that of the smaller vanes. Therefore, it was concluded that the vane size should be at least 100 square inches.

A more complete survey of snow depths than is contained in this report is available from The Canadian Snow Survey, Reference 10. If data from that publication are considered together with the distribution of snow strength shown in Figure 39 of this report, the performance of a wheeled vehicle can be determined to be at least a certain level for all except a certain number of days during the snow season. Figure 39 gives the occurrence of snow strength values where the depth is sufficient to cause "flotation" immobilization. For lesser depths, the probable strength occurrence may be approximated by assuming the usual case of strength proportional to depth. Figure 39 is tentative; it is based on the data presented in this report. Because of the limited number of locations sampled, the data do not describe the geographical boundaries for the occurrence of the strength values shown. However, the "difficult" snow region is approximately the Northern Forest Region (Reference 10), and the locations sampled had been selected as representative of the most "difficult" portions of this region.

While the plate tests have particular application to the performance of wheeled vehicles, the strength values should provide a relative reference for the performance of tracked vehicles. For example, if a particular tracked vehicle

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TABLE 4

SUMMARY OF SHEAR VANE DATA

Date	Tan ϕ_1 (1) 25- and 50-Sq.-In. Vanes		Tan ϕ_2 (3)		Remarks
	Undisturbed	Disaggregated (2)	25- and 50-Sq.-In. Vanes	100-Sq... Vanes	
Houghton					
15 Feb 56	.47	-			
2 Mar "	.62	.43			
7 Mar "	.54	.39			
8 Mar "	.49	.43			
9 Mar "	.36	.29			
10 Mar "	.33	.27			
12 Mar "	.33	.26			
13 Mar "	.28	.25			
15 Mar "	.50	.42			
16 Mar "	.49	.42			
21 Mar "	-	.48			
2 Feb 57	.31	-			
2 " "	.38	-			6" Below Surface (4)
2 " "	.42	-			12" Below Surface
8 Feb 57	.43	-			
8 " "	.50	-			5" Below Surface
8 " "	.50	-			10" Below Surface
13 " "	.30	-			
13 " "	.40	-			6" Below Surface
13 " "	.50	-			12" Below Surface
19 " "	.28	-			
19 " "	.27	-			4" Below Surface
19 " "	.35	-			13" Below Surface
1 Mar "	.42	-			
1 Mar "	.33	-			3" Below Surface
1 Mar "	.37	-			11" Below Surface
6 Mar "	.33	-			
6 Mar "	.35	-			3" Below Surface
6 Mar "	.35	-			10" Below Surface
7 Feb 58	.48				
14 Feb "	.60				
3 Mar "	.54				
29 Jan 59	.47				
4 Feb "	.67				
9 Feb "	.48				
13 Feb "	.39				
16 Feb "	.50				
20 Feb "	.76				
24 Feb "	.40				

Table 4-contd.

Date	Tan φ₁ (1) 25- and 50-Sq.-In. Vanes Undisturbed	Disaggregated (2)	Tan φ₂ (3) 25- and 50-Sq.-In. Vanes	100-Sq.-In. Vane	Remarks
Houghton					
25 Feb 59	.36				
26 Feb "	.39				
25 Jan 60			.37	.45	
28 Jan "			.50	.43	
1 Feb "			-	.35	2" Below Surface
2 Feb "			.33	.43	2" Below Surface
2 Feb "			-	.38	12" Below Surface
4 Feb "			.34	.38	2" Below Surface
4 Feb "			.46	.45	12" Below Surface
5 Feb "			.33	.48	2" Below Surface
8 Feb "			.31	-	2" Below Surface
8 Feb "			.43	.43	12" Below Surface
9 Feb "			.27	.45	2" Below Surface
9 Feb "			.29	.45	12" Below Surface
10 Feb "			.16	.45	2" Below Surface
19 Feb "			.20	.40	2" Below Surface
19 Feb "			.21	.38	12" Below Surface
21 Feb "			.19	.25	2" Below Surface
21 Feb "			.29	.35	12" Below Surface
26 Feb "			.26	.45	2" Below Surface
29 Feb "			.20	.48	2" Below Surface
29 Feb "			.20	.40	12" Below Surface
4 Mar "			.21	.35	2" Below Surface
7 Mar "			.19	.30	2" Below Surface
7 Mar "			.19	.40	12" Below Surface
8 Mar "			.23	.30	2" Below Surface
Quebec					
4 Jan 60	.37				2" Below Surface
1 Mar "	.53				2" Below Surface
Ottawa					
11 Jan 60	.33				2" Below Surface
Kapuskaring					
21 Jan 60	.33				2" Below Surface
7 Mar "	.58				2" Below Surface
9 Mar "	.53				2" Below Surface
Longlac:					
25 Jan 60	.43				2" Below Surface
26 Jan "	.33				2" Below Surface
14 Mar "	.52				2" Below Surface
Ramouski					
18 Feb 60	.25				2" Below Surface

51

should be known to become immobilized at, say, 12 inches of sinkage, then its performance should be relative to the strength value determined from the 6-inch plate, which, according to the method used, is tested to twice its diameter, or 12 inches.

52

501261

SECURITY CLASSIFICATION (if any)

DISPOSITION FORM

FILE NO. TCRAD-CO-OTD 9-97-40-000, Task 4.2	**SUBJECT** Assignment of House Task 4.2, Project 9-97-40-000, Vehicle Mobility Factors
TO Ch/Motor Trans Div	**FROM** CO, TRADCOM **DATE** 1 October 1955 **COMMENT NO. 1** Mr. Davis/6275/ss

1. The following task is assigned to your division for prosecution:

    a. Title: Vehicle Mobility Factors

    b. Task No.: 4.2

    c. Project No.: 9-97-40-000

    d. Date of assignment: 1 October 1955

    e. Target date for completion: To be determined.

    f. Scope:

        (1) To develop correlation factors between mobility of existing vehicles and scaled models on all types of surfaces.

        (2) To record the correlations in a manner that will permit their application to design of future vehicles by first building and testing scaled models to determine relative merits.

    g. Remarks: None

    h. Reference: None.

2. Commercial contracts which are necessary in support of this task will be subject to specific approval. TCTC Contract authority is contained in Task 4, Project 9-97-40-000.

                          /s/   John W. Koletty
                           JOHN W. KOLETTY, Colonel, TC
                           Commanding

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Army Transportation Research
Command, Fort Eustis, Virginia
SCALED VEHICLE MOBILITY
FACTORS (SCALE MODEL TIRES
IN SNOW), by Carlo J. Roma and
Robert P. McGowan. Fourth interim
rept. on Proj. 9R97-40-001-01, H. T.
4.2. Oct 61. 63 p. incl. illus. tables,
10 refs. (TCREC technical rept.
61-118)

Unclassified report

The report covers the testing in snow
of tires having a wide range of width-
(over)

1. Mobility Research

2. Scale Model Test-
   ing

3. Vehicles--Scale
   Model Testing

4. Tires

to-diameter ratios. The performance of two tires for the "ground-supported" (limited snow depth) type of performance is described. Complete "flotation" data from previous years' tests are summarized and further analyzed, and tests of additional "flotation" tests are also discussed. The test results are expressed in dimensionless terms and are applicable for a range of vehicle sizes and weights and of dry snow conditions. Present data are limited to the use of 4x4 vehicles with equal weight distribution. The report shows the possibility for interpreting data from vehicle tests conducted in sand in terms of performance in snow. The results of a preliminary snow survey, which are included in this report, can be used to predict vehicle performance in subarctic below-the-treeline snow regions.

Army Transportation Research Command, Fort Eustis, Virginia SCALED VEHICLE MOBILITY FACTORS (SCALE MODEL TIRES IN SNOW), by Carlo J. Roma and Robert P. McGowan. Fourth interim rept. on Proj. 9R97-40-001-01, H. T. 4.2. Oct 61. 63 p. incl. illus. tables. 10 refs. (TCREC technical rept. 61-118)

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